11-27-2012

Geologic Mapping of the Macon and Moscow SE 7.5-minute Quadrangles with Sedimentological and Petrological Analysis of the Memphis Sand

Candice Fawn Brock

GEOLOGIC MAPPING OF THE MACON AND MOSCOW SE 7.5-MINUTE QUADRANGLES WITH SEDIMENTOLOGICAL AND PETROLOGICAL ANALYSIS OF THE MEMPHIS SAND

by

Candice Fawn Brock

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

Major: Earth Sciences

The University of Memphis

December 2012

ABSTRACT

Brock, Candice Fawn. Degree to be conferred M.S. The University of Memphis. December/2012 degree to be conferred. Geologic Mapping of the Macon and Moscow SE 7.5-minute Quadrangles with Sedimentological and Petrologic Analysis of the Memphis Sand. Major Professor: Dr. Dan Larsen

Detailed geologic mapping of two 7.5-minute quadrangles in Fayette County, Tennessee, and sedimentological analysis of obtained samples of the Eocene Memphis Sand have been performed to assess the locations of Memphis Sand outcrops, whether the facies are stratigraphically continuous in the outcrop region, the depositional characteristics and sediment source of the Memphis Sand, and what can be inferred about direct recharge into the Memphis Aquifer. The Memphis Sand is a fluvial sand with a mixed sediment source that can be separated into the upper, middle, and lower informal members. Direct recharge potential for the Memphis aquifer is limited spatially by the rare, sparse nature of the Memphis Sand outcrops, and by secondary clay accumulation due to soil development on those outcrops.

TABLE OF CONTENTS

List of Figures

Chapter 1: Introduction

This study uses a combination of geologic mapping of the Macon and Moscow SE 7.5-minute quadrangles, sedimentological and petrological evaluation of lithologic units in the map areas, and GIS map analysis to assess recharge to the Memphis aquifer, the stratigraphy of the Eocene Memphis Sand, and the depositional processes of the Memphis Sand in the outcrop region. The two quadrangles selected are located in Fayette County, Tennessee, which is east of Shelby County and the Memphis metropolitan area, and lie within the defined limits of the outcrop zone of the Memphis Sand (Figure 1). This project helps to answer several questions:

- Where are the specific Memphis Sand outcrops?
- Are the facies stratigraphically continuous across the outcrop region?
- What are the depositional characteristics and sediment source of the Memphis Sand?
- What does the map and the sediment analyses tell us about recharge to the aquifer?

This project compares the geologic map created from field mapping with previous maps created using subsurface techniques to improve our understanding of the western boundary of the Memphis Sand exposure belt in western Tennessee. The geologic maps, field descriptions, and sediment analyses are used to describe the stratigraphic character and continuity of the Memphis Sand, address the questions regarding the extension of informal members designated by Hundt (2008) to the exposure belt, and address the

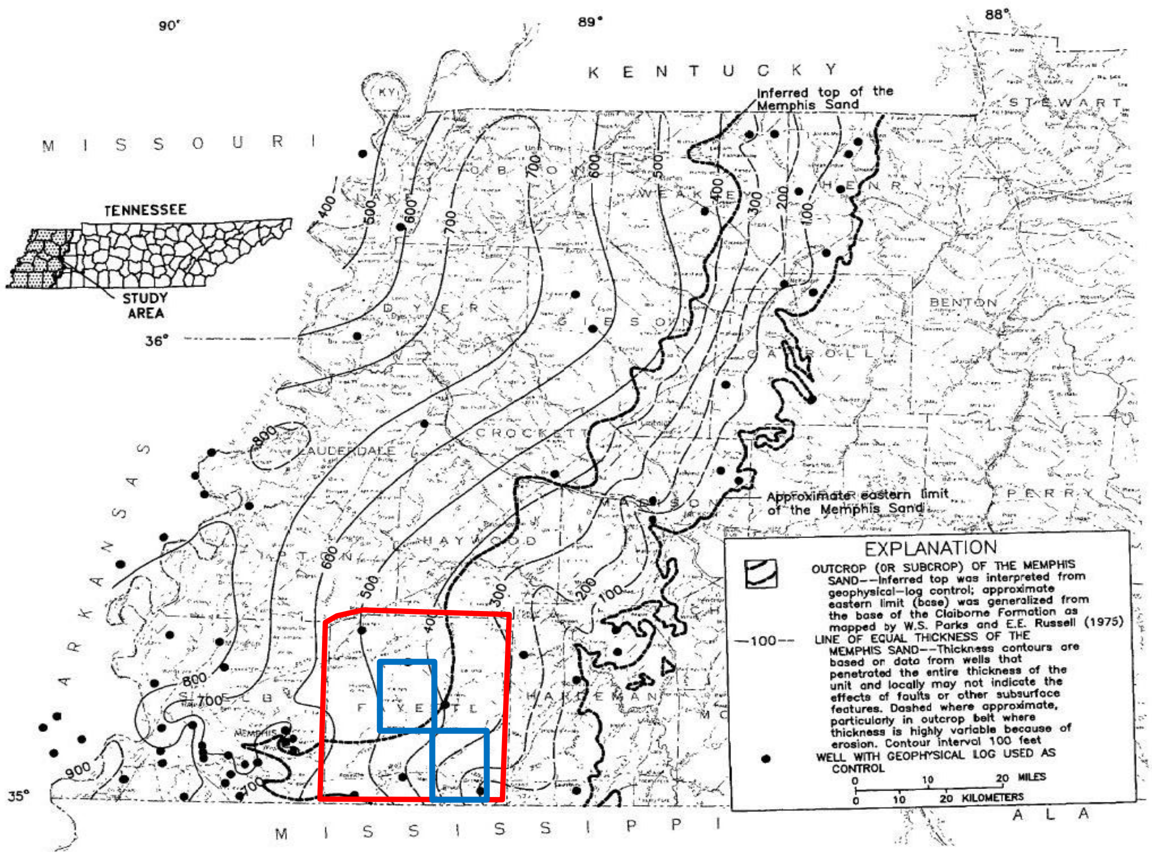


Figure 1. Map, adapted from Parks and Carmichael (1990b), shows the projected outcrop zone of the Memphis Sand across western Tennessee. Fayette County is outlined in red, and the Macon and Moscow SE quadrangles are outlined in blue.

questions regarding the depositional environment and sediment source posed by Lumsden et al. (2009). The sediment descriptions, analyses, and geologic maps are also used to evaluate the probable areas for recharge into the aquifer. According to previous studies of geophysical well-log data and cores done by Cushing et al. (1964), Moore and Brown (1969), Dockery, (1996), Hundt (2008), and a few others the internal stratigraphy of the Memphis Sand is continuous in the subsurface throughout western Tennessee, northern Mississippi and northeastern Arkansas. In most cases the Memphis Sand is overlain by the clay-rich Eocene Cook Mountain Formation, and sand-, silt-, and clay-bearing Eocene Cockfield Formation.

Studies of the depositional environment and petrology of the Memphis Sand evaluated the sand using cores and well-log data (Hundt, 2008; Lumsden et al., 2009; Waldron et al., 2011). The Memphis Sand is predominately massive, laminated, or cross-bedded quartz sand with interbedded clay layers (Parks and Carmichael, 1990a). The environment of deposition of the Memphis Sand is either braided or meandering fluvial and fluvio-deltaic as described by Russell and Parks (1975), Moore (2003), Lumsden et al. (2009). The source of the Memphis Sand is still unknown. No detailed outcrop analysis within the Memphis Sand stratigraphic framework has been done regarding the petrology of the Memphis Sand.

Thus, in this study, 30 outcrop samples were collected for thin section analysis, grain size analysis, and x-ray diffraction to evaluate the petrologic characteristics of the sand and determine the clay mineralogy of the clay facies.

The results are integrated with the previous petrologic knowledge of the Memphis Sand obtained by core and well-log data to more fully understand the depositional setting and sediment source.

The Memphis aquifer, composed of the Memphis Sand, is the most extensive and valuable resource for municipal and industrial potable water in western Tennessee (Parks and Carmichael, 1990a; Webbers, 2003). It is the sole water source for the Memphis metropolitan area. The main recharge zone for the Memphis aquifer is defined as the outcrop region of the Memphis Sand (Figure 1) (Russell and Parks, 1975; Lumsden et al., 2009; Waldron et al., 2011). The rapid rate of urban expansion of the Memphis metropolitan area eastward threatens to impact water supply and quality within the Memphis aquifer (Larsen et al., 2003). Without better defining the recharge zones, urban expansion may begin to cover the critical recharge regions and inhibit or limit recharge. The water quality of the aquifer could also be impacted if the recharge areas remain poorly defined. Therefore, detailed geologic mapping, field descriptions, and sediment analyses are needed in the outcrop region of the Memphis Sand, as exemplified by the Macon and Moscow SE Quadrangles.

Moore (1965) and Parks and Carmichael (1989) used geophysical well-log data to create a map of the “recharge belt” of the Memphis Sand in western Tennessee that shows the projected area where water can directly enter the Memphis aquifer (Figure 1). However, no consideration was taken regarding the influence of the loess or alluvium cover, which is extensive across much of western Tennessee. This study uses geologic mapping focused on the Memphis

Sand to determine locations of actual outcrop. These maps pinpoint areas of potential recharge. In addition, field descriptions and petrologic analysis of samples are used to assess potential for recharge in these locations. Other GIS information, such as soil maps, and GIS tools assist in understanding the potential for recharge in the outcrop region of the Memphis Sand by analyzing the sandy soils and areas of high relief and their relation to recharge.

This thesis is separated into two different publishable documents, chapters two and three. Each of these chapters has its own Introduction, Methods, Results, Discussion, and Conclusion. Chapter one is a general introduction to the overall study. Chapter two is a descriptive document to accompany the maps and addresses questions regarding lithological continuity and recharge potential for the Memphis aquifer based on map distribution of Eocene and Quaternary geologic units. Chapter three focuses on the sedimentology and petrology of the Memphis Sand, and addresses questions regarding depositional environments and provenance of the Memphis Sand as well as post-depositional processes and their impact on infiltration into the Memphis Sand. Chapter three is a manuscript to be submitted to the journal *Southeastern Geology*. Chapter four is a conclusive summary that addresses the questions posed above based on all aspects of the study.

Chapter 2: Map and Stratigraphic Assessment of the Memphis Sand

INTRODUCTION

This document describes and discusses the geologic maps of two 7.5-minute quadrangles in Fayette County, western Tennessee (Figure 2), and their implications for the continuity of the internal stratigraphy of the Eocene Memphis Sand (Figure 3). This paper also addresses direct recharge into the Memphis aquifer, which is primarily composed of the Memphis Sand. The Macon and Moscow SE quadrangles are NW-SE neighbors and contain outcrop of the maximum amount of vertical stratigraphy of the Memphis Sand east of the Memphis area. The quadrangles were chosen based on maps created by Moore (1965) and Parks and Carmichael (1990b) that interpret the projected outcrop region of the Memphis Sand using geophysical well logs. These geologic maps are used to compare field mapping results to maps created using subsurface techniques and improve our understanding of the western boundary of the Memphis Sand exposure belt in western Tennessee. The geologic maps and field descriptions are used to describe the stratigraphic character and continuity of the Memphis Sand and address the questions regarding the extension of informal members, the upper, middle, and lower Memphis Sand members, designated by Hundt (2008). The geologic maps and field descriptions also are used to assess the potential for direct recharge into the Memphis aquifer. The Memphis aquifer provides most of the potable water to the metropolitan area of Memphis, TN, as well as most towns in western TN (Webbers, 2003). Neither of these quadrangles has been previously geologically mapped at the 1:24000 scale, and previous geologic maps pertaining to the area have only been mapped at the state scale (Hardeman et al., 1966).

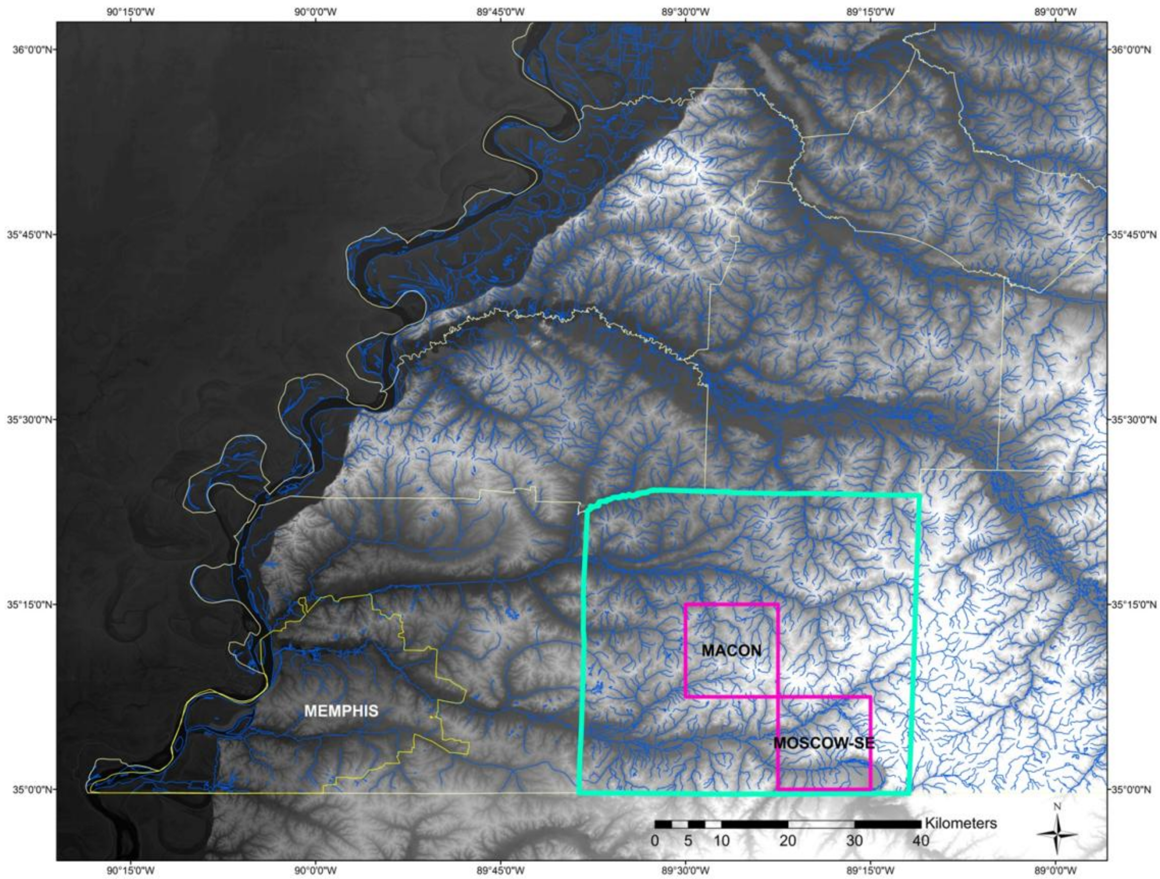


Figure 2. DEM displaying the map areas in Fayette County, outlined in blue, with the two quadrangles, outlined in purple.

ERA	SYSTEM	SERIES	STAGE	Arkansas		Tennessee	Mississippi
				Southern	Northeastern	Western	Northern
				Alluvium	Alluvium	Alluvium	Alluvium
		Holocene			Loess	Loess	Loess
	Quaternary			Terrace	Terrace	Terrace	Terrace
		Pleistocene		deposits	deposits	deposits	deposits
		Pliocene		Upland Complex	Upland Complex	Upland Complex	Upland Complex
			Jackson	Jackson Group		Jackson Fm.	Yazoo Clay
			Group				Moody's Branch Fm.
				Cockfield Formation		Cockfield Fm.	Cockfield Fm.
				Cook Mountain Formation		Cook Mountain Fm.	Cook Mountain Fm.
			Claiborne	Sparta Sand	upper Memphis Sand		Kosciusko Sand
Cenozoic		Eocene	Group	Cane			Zilpha Shale
				River	middle Memphis Sand		Winona Sand
				Formation			Tallahatta Fm.
	Tertiary			Carrizzo Sand	lower Memphis Sand		Meridian Sand
					Flour Island	Flour Island	Hatchetigbee Fm.
			Wilcox		Formation	Formation	Bashi Fm.
			Group	Undifferentiated			Tuscahoma Fm.
					Fort Pillow Sand	Fort Pillow Sand	Nanafalia Fm.
					Old Breastworks	Old Breastworks	Naheola Fm.
		Paleocene	Midway	Porters Creek Fm.	Formation	Formation	
			Group		Porters Creek Fm.	Porters Creek Clay	Porters Creek Fm.
				Clayton Formation		Clayton Fm.	Clayton Fm.

Figure 3. A stratigraphic column from Waldron et al. (2011) showing the Cenozoic stratigraphy in the northern Mississippi embayment. The Memphis Sand and correlative strata in Arkansas and Mississippi are also shown.

METHODS

Field mapping, ArcGIS digitization, and other ArcGIS analyses were used to create maps for the Macon and Moscow SE Quadrangles. The maps are accompanied by geologic cross-sections created using NeuraLog and NeuraSection software. For field mapping, accessible areas were traversed, geologic exposures were described in the field, and the identified formations and geomorphic terraces and alluvial fans were mapped on a field map. Quaternary and Eocene geologic units were distinguished based on texture, color, and compositional characteristics. The loess was identified as brown massive silt to very fine sand. The alluvium was identified as yellowish brown to brown very fine to coarse sand and gravel that is massive, cross-bedded, or laminated. The Cockfield formation was identified as interbedded white clay and yellowish-orange to red, fine to medium sand that is massive, cross-bedded, or laminated. The Cook Mountain formation was identified as massive white silty clay. Although it was not seen in the map areas, it was observed in exposures in eastern Shelby County. The Memphis Sand was identified as massive, cross-bedded, or laminated, reddish to yellowish-orange, fine to coarse sand. Rare white or grayish-white clay beds range from less than a centimeter to a few meters thick. In many of the Memphis Sand exposures, a terrace gravel layer, less than 2 m thick, overlies the Memphis Sand. Measurements such as strike and dip were also taken in the field.

The field map data were digitized using the ESRI ArcGIS 10 software. Polygons were created to represent each of the geologic map units. The digitized polygons were projected onto the World Topographic base map using the WGS 1984 Mercator Auxiliary Sphere projection. The polygons were used to calculate the potential area for recharge into the Memphis Aquifer. ArcGIS was also used to evaluate soil maps provided by the Tennessee Soils Survey and geomorphic features observed from aerial photos, topographic maps, and digital elevation models (DEMs) provided by the USGS website. These were all re-projected into the WGS 1984 Mercator Auxiliary Sphere projection. The soils maps and DEMs were overlain using ArcMap 10's Spatial Analysis (to manipulate the raster file for slope), Conversions (to create a polygon from the raster slope file), and Overlay (to spatially join and clip the sandy soils and high slope polygons) functions to show if any relation between the slope and the sandy soil types predetermine the locations of Memphis Sand outcrops. The figure created from these layers was compared to the digitized field map data to determine the degree of correlation between them. The soils maps were also used independently to evaluate places of potential recharge by isolating the sandy soils. The maps were also used to calculate the percentage of area underlain by the Memphis Sand, alluvium, sandy soils, and sandy soils in high relief for each of the two quadrangles. Aerial photos and topographic maps were overlain to evaluate the distribution of geomorphic features such as alluvial fans and terraces because they are difficult to determine in the field.

The geologic cross-sections were created using Neurasection software and four wells per quadrangle. The cross-sections have a NW-SE orientation, perpendicular to the regional strike. The cross sections provide subsurface control of the map distribution of the Memphis Sand and other Eocene units. Eight Phillips Petroleum well logs were used that range from 200-300 feet in depth. Digitized .las log files were obtained from (Crone, 2010) using one of her geologic cross-sections that extended from Shelby County into the Moscow SE Quadrangle in Fayette County. The units on the cross-sections are selected based on the respective tops of geologic formations identified by Hundt (2008). The loess had a clay-like response, the Memphis Sand had a thick cylindrical sand response, and the Flour Island (Figure 3) has thick simple clay response. The well data from the cross-section in Neurasection were exported into ArcGIS to create a point file and location map for the area. ArcGIS was also used to check the well elevations from the log headings against a 10-meter digital elevation model (DEM) obtained from the USGS Seamless Server to correct for inaccuracies.

RESULTS

Geologic maps of the Macon 7.5-minute Quadrangle and the Moscow SE 7.5-minute Quadrangle are shown in Plate 1 and Plate 2; overlays of the geologic units on the sandy soil maps are shown in figures 4 and 5. The quadrangles follow the northwest dip direction of Tennessee strata in the Mississippi Embayment and expose most of the thickness of the Eocene Memphis Sand (Cushing et al., 1964).

Eocene strata crop out sparingly in ravines and valley walls throughout the Macon Quadrangle. In the northwestern corner of the quadrangle (Plate 1) the Eocene Cockfield Formation crops out in a ravine and is composed primarily of interbedded sands and silty clays with the sands being the more dominant lithology. The Cockfield typically overlies the Eocene Cook Mountain Formation, which was observed in a ravine several km west of the map area. This unit is composed of interbedded silty clays and sands with the silty clay being the more dominant lithology. The Cook Mountain Formation was not observed in the map area possibly due to its discontinuous nature in southwestern Tennessee (Crone, 2010). The upper Memphis Sand is observed sparingly in ravines and rare hill or valley wall exposures across a majority of the Macon quadrangle (*sensu* Hundt, 2008; Waldron et al., 2011). The upper Memphis Sand is characterized as massive, laminated, or cross-bedded fine to coarse quartz sands with sparse silty clay clasts or rare thin silty clay beds (Figure 6). The middle Memphis Sand is observed in the southeast corner of the quadrangle. The middle Memphis Sand is characterized as having two thick continuous silty clay beds at the upper and lower designations of the section with an intervening interval of interbedded massive, laminated, or cross-bedded very fine to medium sands and common silty clay beds, comparable to descriptions by Hundt (2008) and Waldron et al. (2011).

Within a majority of the Memphis Sand exposures, the upper 1 to 2 m expose a distinct series of sand beds that contain common chert gravel with angular to subangular pebbles of goethite-cemented sand (Figure 6). Although these gravelly sand deposits are found throughout the map area, they are too discontinuous in distribution and thin to be mapped separately at the 1:24,000 scale, so they were included with the Memphis Sand because of their lithologic similarity and close association.

Quaternary deposits are widespread within most of the Macon Quadrangle. The Quaternary loess covers a majority of the upland areas. The loess is characterized as a massive brown silt layer (Figure 6) that covers much of western Tennessee and thins to the east. Quaternary alluvium fills much of the stream valleys. The alluvium is characterized by brown to yellowish-brown massive, laminated, or cross-bedded very fine to coarse sands, silt, clay (Figure 6), and common gravel in the lower coarser grained alluvium.

In the Moscow SE Quadrangle, Plate 2, the middle Memphis Sand (Hundt, 2008; Waldron et al., 2011) is observed in the northern and central portion of the map, and the upper part of the lower Memphis Sand is found in the southeastern portion of the map. The lower Memphis Sand is characterized by massive, laminated, or cross-bedded fine to medium micaceous quartz sands with few silty clay clasts and thin silty clay beds. The Eocene exposures are found primarily in ravines and along valley walls. The most extensive exposure of the Memphis Sand is along the north side of the Wolf River valley in the southeastern part of the map.

Much like that observed in the Macon Quadrangle, the loess covers much of the upland areas in the Moscow SE quadrangle. The loess in this quadrangle differs somewhat from the loess in the Macon quadrangle in that it is thinner overall and tends to be somewhat sandy in places where it overlies the Memphis Sand or alluvium.

In the Moscow SE quadrangle alluvium fills much of the lower-order stream valleys. Fluvial terraces and alluvial fans are present in the valleys and low valley walls along both the North and South forks of the Wolf River. Four terrace levels are observed across the map area with the highest terraces observed along the south fork. The elevation ranges of the terraces from youngest to oldest (T1-T4) are 3 -6 m, 8-9 m, 15 m, and 18 m above the modern floodplain. The terraces and alluvial fans were determined primarily using the maps and ArcGIS. Because of vegetation cover, lithologic descriptions from the field are limited, but the terraces are similar to the coarser grained upper alluvium with abundant gravel and coarser sands. The alluvial fans are fairly small and resemble the lower alluvium with finer sands, silts, and possibly silty clay.

Figures 4 and 5 show maps of the Macon and Moscow SE quadrangles that have been overlain by the sandy soils obtained from the National Resource Conservation Service maps for the area. These figures show that sandy soils are primarily found in high relief areas, such as incised stream valleys and steep valley walls, as well as terraces, alluvial fans, and parts of the areas covered by alluvium.

In the Macon quadrangle the percent underlain by the Memphis Sand is 0.2 %, and the percent underlain by the alluvium is 18.5 %. In the Moscow SE quadrangle the percent underlain by the Memphis Sand is 0.8 %, the percent underlain by the alluvium is 20.1 %, and the percent underlain by the alluvium including the alluvial fans and terraces is 26.9 %. Total area underlain by sandy soils in the Macon quadrangle is 6.0 %, whereas 7.2 % is covered by sandy soils

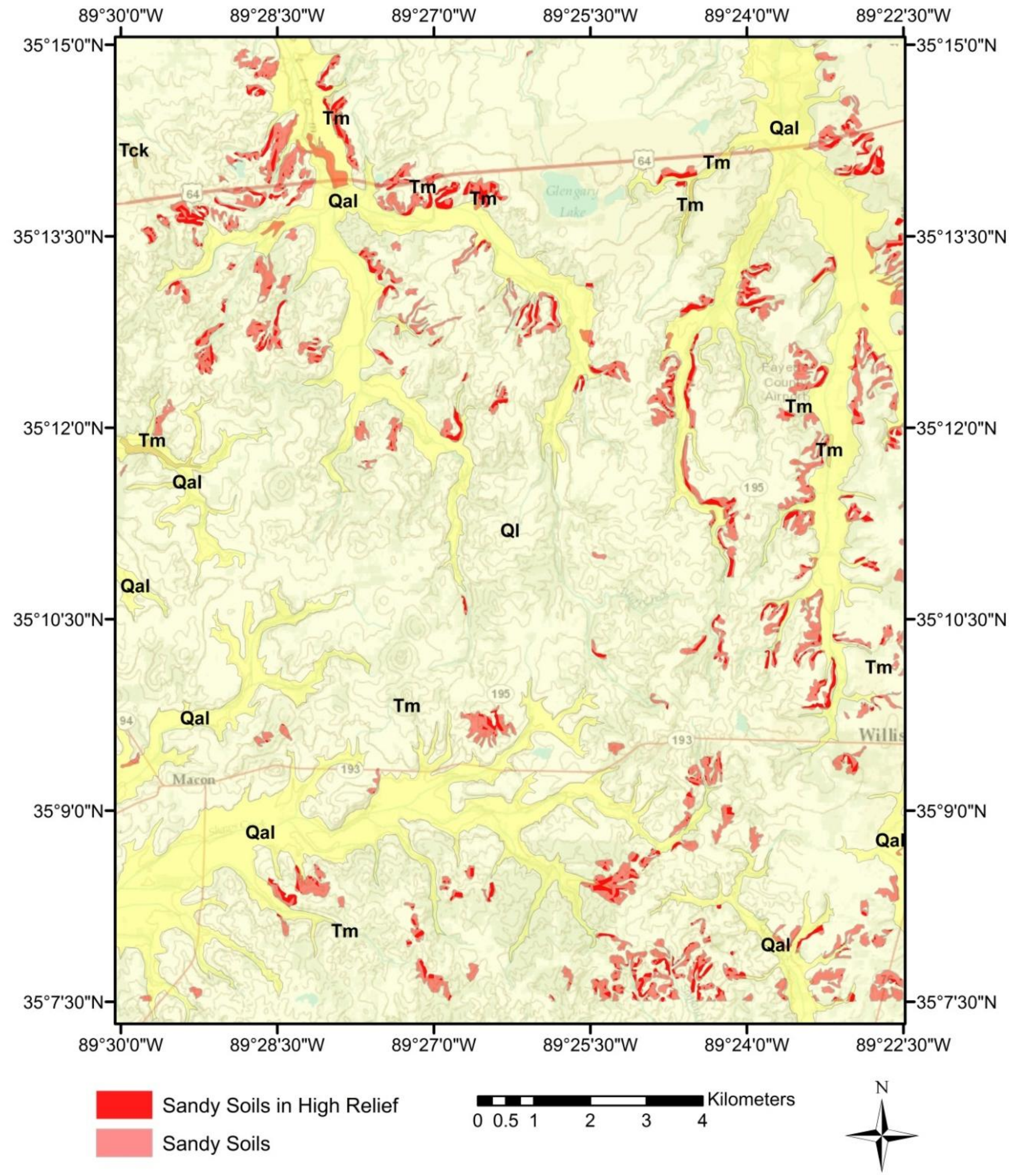


Figure 4. Map of the Macon 7.5-minute quadrangle displaying the sandy soils and sandy soils with high relief polygons. See Plate 1 for legend concerning the geologic units.

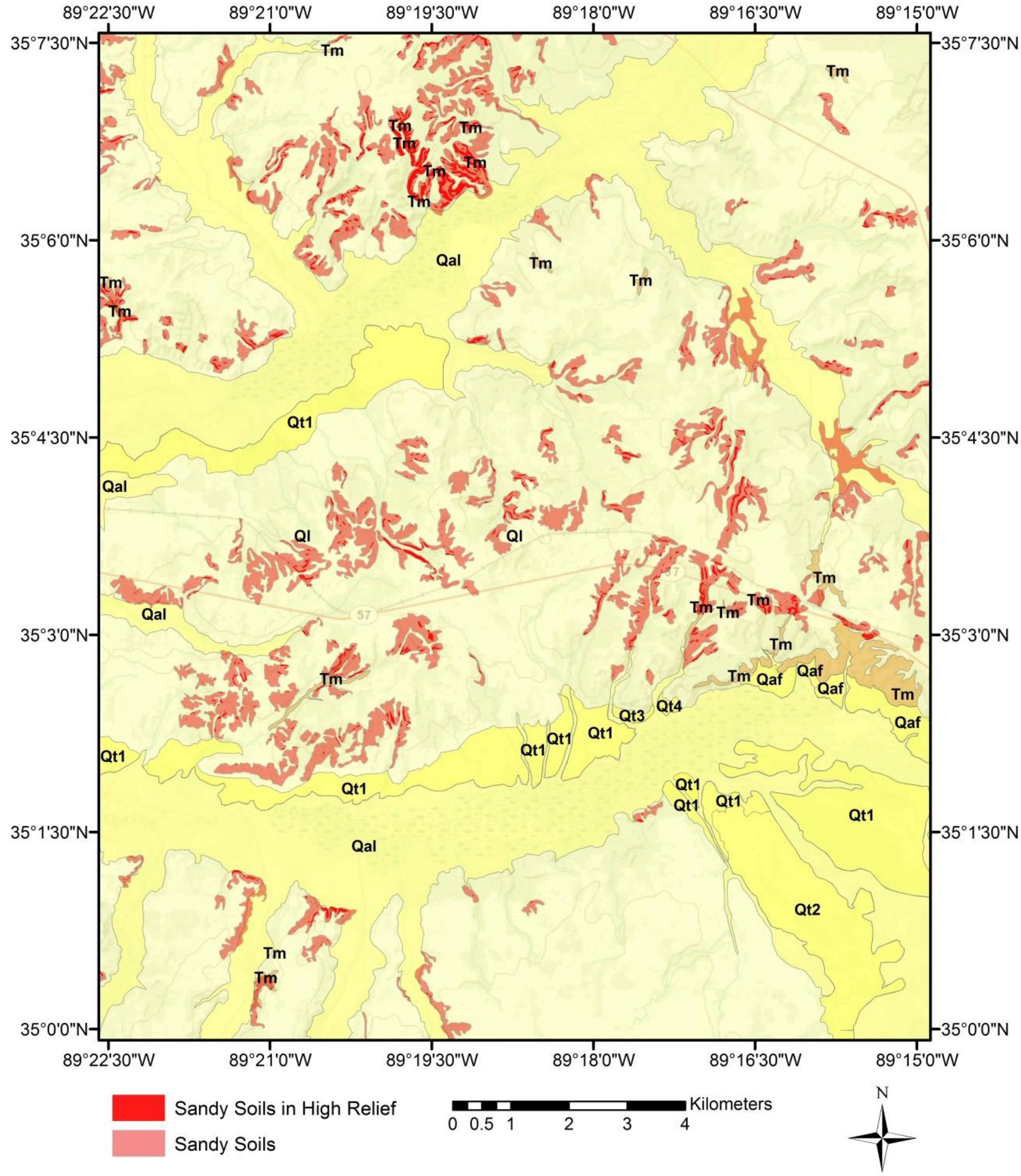


Figure 5. Map of the Moscow SE 7.5-minute quadrangle displaying the sandy soils and sandy soils with high relief polygons. See Plate 2 for legend concerning the geologic units.

in the Moscow SE quadrangle. Total area in the Macon quadrangle covered by sandy soils with high relief is 1.2 %, compared to 0.7 % in the Moscow SE quadrangle.

DISCUSSION

In the Macon and Moscow SE quadrangles (Plate 1 and Plate 2) the lowermost Eocene Cockfield Formation and Eocene Memphis Sand (Figures 6c and 6e) crop out sparingly, primarily in upland incised sandy bottom stream valleys and less commonly along valley walls of larger streams. Discontinuous remnants of gravelly sand interpreted as late Cenozoic fluvial terrace deposits are observed with many of the Memphis Sand outcrops. These deposits are well oxidized, similar to the upper exposures of the Memphis Sand, but contain chert gravel and iron oxide concretions (Figure 6a). They are found typically overlying the Eocene Memphis Sand, but underlying either the Quaternary loess or alluvium. Based on lithology and similarity of elevation, these terrace gravels are correlated with the Upland Complex (Van Arsdale et al., 2008). The Upland complex is interpreted as a Pliocene high-level terrace complex that overlies the Tertiary units and underlies the Loess and modern Alluvium along the current Mississippi River from Illinois to Louisiana. It is characterized as a fluvial chert gravel commonly with limonite coatings and fine to coarse sands (Van Arsdale et al., 2008).

The lowland muddy bottom stream valleys are covered with Quaternary alluvium (Figure 6b). The higher order stream valleys of the Wolf River are

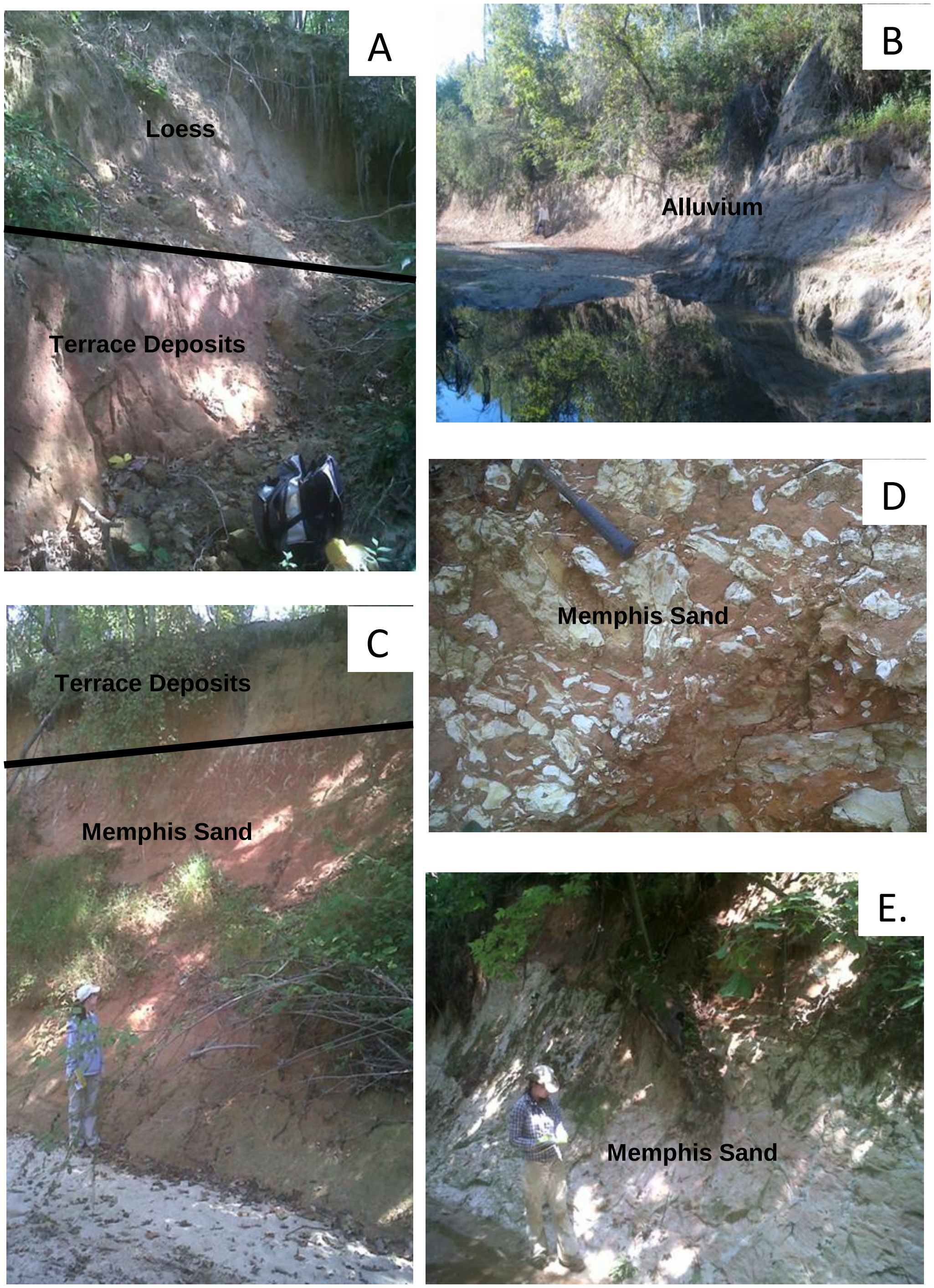


Figure 6. Photos of the typical outcrops for the Memphis Sand and other units. A. The terrace deposits overlain by loess. B. The fine grained alluvium with standing water. C. The Memphis Sand overlain by the terrace deposits. D. Brecciated clay intraclasts found in Memphis Sand outcrops. E. A >2m thick silty clay bed found in the Memphis Sand.

covered with Quaternary alluvium, terraces, and small alluvial fans along the valley margins. The lower two terrace levels (T1 and T2) are at elevations that correlate to the Finley and Hatchie terraces (Saucier, 1987). Saucier (1987) mapped the Finley terrace elevation 3 to 7 m above the modern floodplain level, and T1 mapped in the Moscow SE quadrangle ranges from 3 to 6 m above the modern floodplain. The T2 terrace mapped in the Moscow SE quad ranges from 8 to 9 m above the modern floodplain, which is slightly lower than the 10 to 15 m levels mapped by Saucier (1987). However, in some of the larger streams the average Hatchie terrace elevations are slightly lower in the upstream reaches (Saucier, 1987). T1 and T2 are both large and relatively continuous along the Wolf River. The Humbolt and Henderson terraces are the two older terraces mapped by Saucier (1987) with elevation ranges 10 to 20 m above the modern floodplain and greater than 20 m above the modern floodplain, respectively. Neither of these terraces is mapped by Saucier along the Wolf River, and the Henderson terrace is only mapped along the upstream parts of the Deer Fork River. These terraces are both relatively discontinuous and the Humbolt terrace is best exposed in northwestern Tennessee streams. The elevations of T3 and T4 in the Moscow SE quad are 15 and 18 m, respectively, and therefore most likely correlate to the Humbolt terrace.

Previous work has shown that the Memphis Sand is comprised mainly of fluvial sand, but has at least two laterally persistent clay-dominated intervals that divide the Memphis Sand into three informal members, upper, middle, and lower Memphis Sand (Hundt, 2008; Lumsden et al., 2009). These clay units are correlated to the Zilpha Clay and Basic City Shale of Mississippi (Hundt, 2008; Waldron et al., 2011). Exposures of clay facies in the southeastern Macon Quad and south-central Moscow SE Quad maps are consistent with the clay intervals observed by Hundt (2008) and Waldron et al. (2011) and support the extension of the tripartite stratigraphy of the Memphis Sand to surface exposures. In the northern portion of the Macon Quad the exposure consist mostly of cross-bedded sands with some massive sand exposures as well. Grains were fine to coarse, poor to well sorted equant quartz sands consistent with grain compositions in the upper Memphis Sand. In the southern portion of the Moscow SE Quad exposures exhibited characteristics of the lower Memphis Sand and were massive or cross-bedded fine to coarse, poor to well sorted equant micaceous quartz sands.

GIS analysis of geology, soils and topographic data show areas most likely to facilitate recharge into the aquifer in the two mapped quadrangles. The Memphis Sand comprises most of the Memphis aquifer. Moore (1965) and Parks and Carmichael (1990b) developed maps showing the estimated recharge area of the Memphis Sand as a wide continuous band across a portion of western Tennessee. However, the results of this study indicate that the Memphis Sand crops out only in specific areas and, thus, opportunities for direct recharge to the aquifer are limited. Although the Memphis Sand is continuous in subcrop throughout the map areas, the majority of the two map areas are covered by Pleistocene Loess in the upland areas. Valley floors are capped by silty Quaternary alluvium, but include sandier alluvial fan and terrace deposits along larger streams, such as the Wolf River. Upland, sand-bottom streams are almost always dry except after a rain storm, whereas lowland silt-bottom streams are almost always wet even after weeks without substantial rain. These observations suggest that the upland stream channels may provide another avenue of recharge to the aquifer. Studies performed by Waldron and Larsen (Personal communication, D. Larsen) at Pinecrest, a site in the Moscow SE quadrangle, found the upland streams recharge the aquifer by seepage into sandy stream beds.

Maps were created using ArcGIS to overlay of the sandy soils and sandy soils with areas of high relief. The percent areas for the Memphis Sand and sandy soils with high relief are comparable in both map areas. In the Macon quadrangle there is a 1.0 % difference which could indicate either more possible Memphis Sand outcrop locations or areas where the alluvium is incised but no Memphis Sand is exposed. However, it shows there is a possible relationship between the outcrops of Memphis Sand available for recharge and amount of incision in that quadrangle. In the Moscow SE quadrangle there is a 0.1 % difference between the areas underlain by the Memphis Sand and the sandy soils with high relief. This could relate to the loess being thinner in this map area suggesting that less incision is required to expose the sand. The maximum possible recharge to the Memphis Aquifer in the Macon quadrangle would be about 18.7 % of the map area including both the alluvium and Memphis Sand exposures, but if only the sandy soils were taken into account the percent area possible for recharge would be 6.0 %. The maximum possible recharge to the

Memphis Aquifer in the Moscow SE quadrangle would be about 27.7 % of the map area including all of the alluvium and Memphis Sand, but if only the sandy soils were taken into account here the percent area available for recharge would only be 7.2 %.

CONCLUSION

The Eocene Memphis Sand crops out sparsely in the Macon and Moscow SE quadrangles. It primarily crops out in upland incised sandy bottoms streams and rarely along valley walls of larger streams. Overlying the Memphis Sand is a reworked terrace gravel layer potentially related to the Upland Complex that exhibits many of the same characteristics of the Memphis Sand and contains chert and/or iron oxide gravels. Quaternary loess and alluvium cover most of the map areas except where the land surface is deeply incised. Along the Wolf River in the Moscow SE quadrangle, geomorphic features such as fluvial terraces and alluvial fans are present.

In the southeastern portion of the Macon quadrangle and the northern portion of the Moscow SE Quadrangle thick (>1 m) clay beds outcrop in the Memphis Sand. These clay layers are consistent with the clay layers observed by Hundt (2008), and reinforce the tripartite division of the Memphis Sand into upper, middle, and lower Memphis Sand proposed by Hundt (2008) and Waldron et al. (2011). Observations made in the northern portion of the Macon quadrangle show sands that are cross-bedded or massive fine to coarse grain, poor to well sorted equant quartz sands which is consistent with the characteristics of the upper Memphis Sand. In the southern portion of the Moscow SE quadrangle outcrops are massive or cross-bedded, fine to coarse, poorly to well sorted micaceous quartz sands which is consistent with the lower Memphis Sand characteristics.

Opportunities for direct recharge into the Memphis Aquifer are limited because the Memphis Sand crops out only in specific areas such as upland incised sandy bottom streams. However, recharge can occur in areas covered by coarse alluvium and stream terraces. GIS Analysis of the map areas and soils maps suggests that an average of 6.6 % of the surface area in the two quadrangles provides a direct recharge to the Memphis aquifer, based on the amount of exposure of Memphis Sand and sandy soils.

Chapter 3: Sediment and Petrologic Analysis of the Memphis Sand

INTRODUCTION

The Eocene Memphis Sand is the lithostratigraphic unit comprising the Memphis aquifer, the source of potable water for much of western Tennessee including Memphis and the surrounding metropolitan area (Parks and Carmichael, 1990a). As urban expansion over potential recharge areas and contamination may threaten the sustainability of the water supply from the aquifer, a better understanding of the aquifer's sedimentary and petrologic properties is needed. Few studies have been performed to evaluate and understand the sedimentologic and petrologic characteristics of the Memphis Sand (Lumdsen et al., 2009). In this study, the sedimentology and petrology of the Memphis Sand in surface exposures is investigated to better understand recharge processes for a clastic groundwater reservoir as well as to understand the continuity of the internal stratigraphy of the Memphis Sand. Also, insight to the potential provenance of the Memphis Sand is addressed using the petrologic and mineralogical characteristics.

The study area focuses on two 7.5-minute quadrangles, the Macon and Moscow SE quadrangles, in Fayette County located in western Tennessee, east of Memphis and Shelby County (Figure 7). The two quadrangles are NW-SE neighboring quads that transect the projected outcrop region of the Memphis Sand perpendicular to the regional strike in the Mississippi embayment (Parks and Carmichael, 1990b).

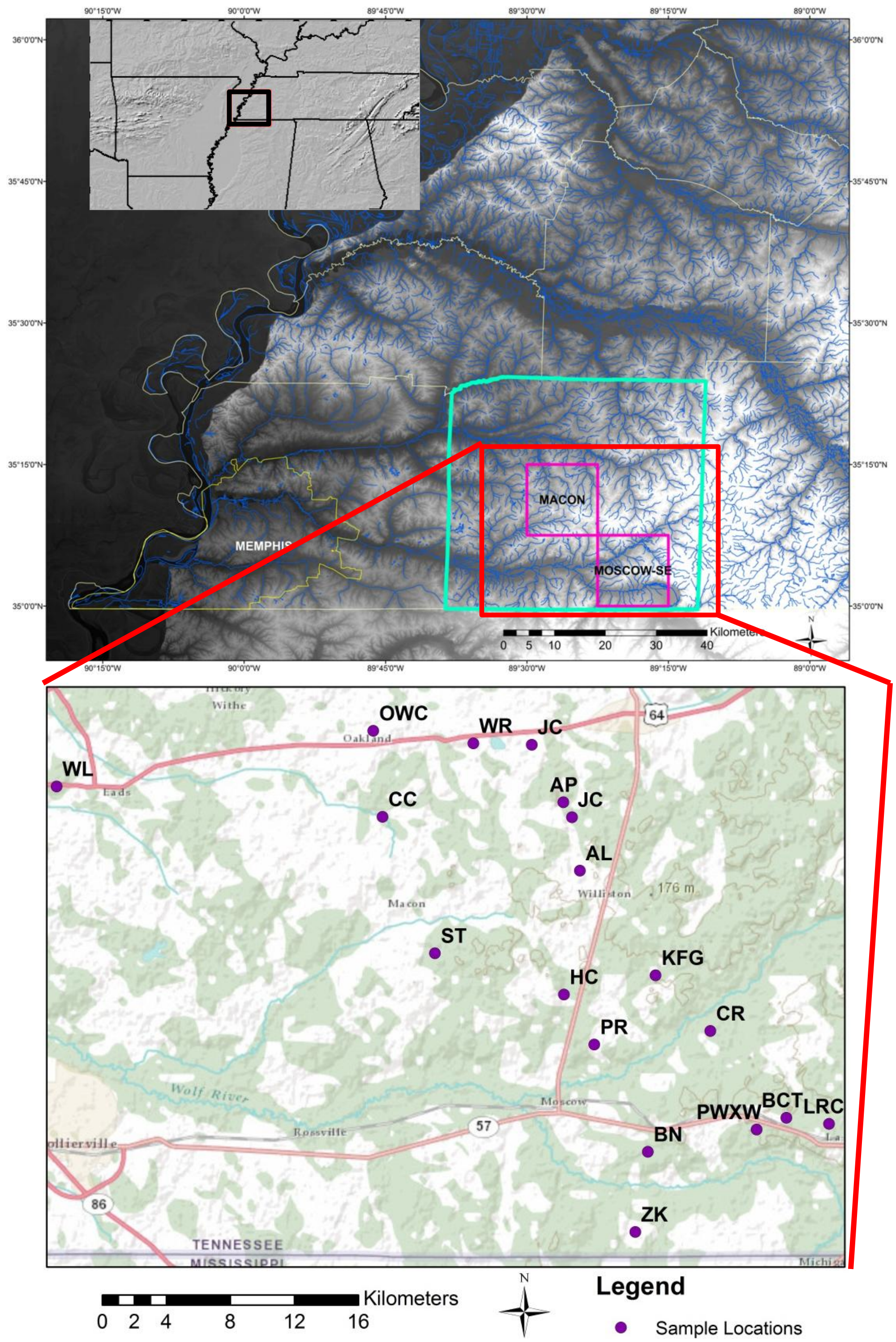


Figure 7. Locations of samples are represented by a purple dot on the World Topographic Map provided by ArcGIS. The inset map was created using DEMs obtained from the USGS seamless server. Fayette County is outlined in aqua and the two quadrangles are outlined in pink.

Samples of the Memphis Sand and associated deposits were collected primarily from exposures in incised stream valleys during field mapping. Field descriptions, thin section analysis, grain size analysis, and x-ray diffraction were conducted to evaluate the petrologic and sedimentologic characteristics of the Memphis Sand. The petrology and sedimentology are used to help evaluate continuity of the internal stratigraphy of the Memphis Sand with emphasis on the tripartite division of the Memphis Sand into informal upper, middle, and lower members (Hundt, 2008 and Waldron et al., 2011). The Memphis Sand is composed of unconsolidated interbedded sands, silts, and clays with minor lignite and is of fluvial to fluvio-deltaic origin (Moore et al., 2003; Gentry et al., 2006; Lumsden et al., 2009); however, little is known regarding the details of these depositional processes or how the depositional environments changed through the depositional history of the Memphis Sand. The petrologic and sedimentologic characteristics of the Memphis Sand are also used to assess the potential for recharge of the Memphis aquifer in the outcrop region. It is important to understand the recharge properties of the Memphis Sand in outcrop because areas available for direct recharge are limited in the region (Brock and Larsen, 2010; Brock and Larsen, 2011).

BACKGROUND

The Eocene Memphis Sand is the lower lithostratigraphic unit of the Claiborne Group in the northern Mississippi Embayment (Figure 8) (Cushing et al., 1964; Hosman, 1996; Waldron et al., 2011). The Memphis Sand in the subsurface is overlain by the Eocene Cook Mountain and Cockfield formations, and is underlain by the Flour Island Formation of the Wilcox Group (Parks and Carmichael, 1990a). The Memphis Sand ranges from 0 to 275 m thick and is thinnest along the eastern margin of the outcrop zone and thickest in southwestern Shelby County (Moore, 1965; Parks and Carmichael, 1990a; Waldron et al., 2011). The Memphis Sand is further subdivided in Mississippi and Arkansas (Figure 8). In northern Mississippi, the correlative interval of the Claiborne Group is subdivided into the Kosciusko Sand, Zilpha Clay, Winona Sand, Tallahatta Formation, and Meridian Sand (Dockery, 1996). In southeastern Arkansas, the correlative interval of the Claiborne Group is subdivided into the Sparta Sand, Cane River Formation, and Carrizo Sand (Cushing et al., 1964; Hosman, 1996; Waldron et al., 2011).

Hundt (2008) and Waldron et al. (2011) divide the Memphis Sand into three separate informal members based on two thick clay units separating the upper, middle, and lower parts of the formation. These clay facies are found at the top and bottom of the middle Memphis Sand and tentatively correlated to the Zilpha Clay and Basic City Member of the Tallahatta Formation. Waldron et al. (2011) observed that the tripartite division of the Memphis Sand is mappable in the subsurface over the three state region of Arkansas, Tennessee, and Mississippi. Hundt (2008) correlates the upper Memphis Sand to the Kosciusko Sand of Mississippi and Sparta Sand of Arkansas, the upper clay layer of the middle Memphis Sand to the Zilpha Clay found in Mississippi, the lower continuous clay layer of the middle Memphis Sand to the Basic City Shale, a member of the Tallahatta Formation which also correlates well with the lower part

ERA	SYSTEM	SERIES	STAGE	Arkansas		Tennessee	Mississippi
				Southern	Northeastern	Western	Northern
				Alluvium	Alluvium	Alluvium	Alluvium
		Holocene			Loess	Loess	Loess
	Quaternary			Terrace	Terrace	Terrace	Terrace
		Pleistocene		deposits	deposits	deposits	deposits
		Pliocene		Upland Complex	Upland Complex	Upland Complex	Upland Complex
			Jackson	Jackson Group		Jackson Fm.	Yazoo Clay
			Group				Moody's Branch Fm.
				Cockfield Formation		Cockfield Fm.	Cockfield Fm.
				Cook Mountain Formation		Cook Mountain Fm.	Cook Mountain Fm.
			Claiborne	Sparta Sand	upper Memphis Sand		Kosciusko Sand
Cenozoic		Eocene	Group	Cane			Zilpha Shale
				River	middle Memphis Sand		Winona Sand
				Formation			Tallahatta Fm.
	Tertiary			Carrizzo Sand	lower Memphis Sand		Meridian Sand
					Flour Island	Flour Island	Hatchetigbee Fm.
			Wilcox		Formation	Formation	Bashi Fm.
			Group	Undifferentiated			Tuscahoma Fm.
					Fort Pillow Sand	Fort Pillow Sand	Nanafalia Fm.
					Old Breastworks	Old Breastworks	Naheola Fm.
		Paleocene	Midway	Porters Creek Fm.	Formation	Formation	
			Group		Porters Creek Fm.	Porters Creek Clay	Porters Creek Fm.
				Clayton Formation		Clayton Fm.	Clayton Fm.

Figure 8. A stratigraphic column from Waldron et al. (2011) showing the Cenozoic stratigraphy in the northern Mississippi embayment. The Memphis Sand and correlative strata in Arkansas and Mississippi are also shown.

of the Cane River Formation in Arkansas, and the lower Memphis Sand to the Meridian Sand in Mississippi and Carrizzo Sand in Arkansas.

The Memphis Sand comprises the main lithostratigraphic unit of the Memphis aquifer. Studies using geophysical well log data performed by Moore (1965) and Parks and Carmichael (1990a) project subsurface data to the outcrop or recharge region of the Memphis aquifer in western Tennessee. The recharge zone of the Memphis aquifer is defined where the aquifer is unconfined in western Tennessee. The Memphis aquifer is a highly permeable and porous groundwater reservoir that has an extremely large storage capacity and underlies about 19,166 square kilometers of western Tennessee (Moore, 1965). The Memphis aquifer is the most extensive and valuable resource for potable water in western Tennessee and is the sole water source for the Memphis metropolitan area (Parks and Carmichael, 1990a; Webbers, 2003).

Lumsden et al. (2009) interpreted the Memphis Sand to be an unconsolidated to semi-consolidated quartz arenite or quartz wacke. The weak cementation of the sediment is attributed primarily to a secondary clay matrix, but in rare cases iron oxide cementation is present. Much of the formation is dominated by fine to coarse grained massive, laminated, or cross-bedded sands that are poorly to well sorted. Sedimentary features in the sands include cut and fill crossbedding, rip ups, and armored mudballs. The bedding characteristics and grain-size data suggest deposition in either a meandering or braided fluvial environment (Lumsden et al. 2009). This is consistent with the regional Gulf Coast stratigraphic interpretations that indicate correlative units are fluvio-deltaic to marginal marine in origin in Mississippi (Mancini and Tew, 1991). Monocrystalline quartz tends to be angular to sub angular, and polycrystalline quartz tends to be subrounded to rounded. Trace amounts of kyanite and zircon are observed throughout and some sands are micaceous. Chert and iron oxide pebbles are locally present amongst the sand. Porosity of the sand is about 30 to 50 % (Lumsden et al., 2009). The clay minerals are mostly kaolinite, illite, and smectite. Prior studies of the clay mineralogy in other parts of western Tennessee state that clay beds are predominately kaolinite with minor amounts of illite (Jeffers, 1982; White, 1985).

The source of the Memphis Sand is still debated. It is likely that the source of the sands is from either the Appalachian Mountains or Ozark Mountains. Lumsden et al. (2009) proposed that the source is predominately the St. Francois region of the Ozark Mountains in Missouri. They argue the source must be volcanic in origin with influences of mixed metamorphic, igneous, and sedimentary rocks. Also, due to the amount of embayed monocrystalline quartz and its angularity, they argue the source area must be relatively close. Another suggestion for the provenance of the Memphis Sand is the southern Appalachian Mountains in the Blue Ridge and Piedmont Plateau regions (Pryor and Glass, 1961; Potter and Pryor, 1964). Potter and Pryor (1964) argue that the southern Appalachian Mountains are most likely the source based on accessory mineral types and paleocurrent analysis; whereas, Pryor and Glass (1961) focused on the clay mineralogy and agree that the southern Appalachian Mountains are the most likely source. Others propose that the Memphis Sand is a result of reworked Cretaceous Tuscaloosa formation (Marcher and Stearns, 1962) or that the Memphis Sand has a mixed source area of both reworked Cretaceous Tuscaloosa Formation and the Ozark Mountains of Missouri (Hundt, 2008).

METHODS

A total of 40 samples were collected from 18 different locations (Figure 7). Field descriptions and lab descriptions included bulk color and variations or mottling (using the Munsell color designations), visual estimation of grain size, range and sorting, grain composition, shape and angularity, sedimentary structures, cementation, and carbonate content. Field descriptions also included general sedimentological descriptions including bedding structures, bedding contacts, and sedimentary facies relationships.

Field description of a soil profile on the Memphis Sand included moist/wet color, mottling, structure, consistency, texture, gravel content, clay content, roots, pores, pH and $CaCO_3$ content. Along with the descriptions, a sodium dithionite method for removal of Fe oxides and hydroxides (Gee and Bauder, 1986) was conducted samples from the soil profile prior to sand, silt, clay particle size analysis.

Sediment samples were used for lab analyses including particle size analysis, x-ray diffraction (XRD), and thin section petrography. Particle size analysis (adapted from Gee and Bauder, 1986) was used to assess the coarse-fraction (> 63 micron) size distribution of 28 sand-rich samples.
X-ray diffraction analysis of the clay-size fraction was done on 5 clay-rich samples to determine the clay mineralogy. Clay was separated and prepared by

being disaggregated, centrifuged, collected on a 0.45 µm filter using a vacuum and carefully transferred to a glass slide. XRD was performed on each sample under air dried and ethyl glycol solvation conditions. The XRD settings were Cu Kα radiation at 40 kV and 40 mA, samples scanned from 3 to 45° 2-theta with a step of 0.4° 2-theta and scan speed of 0.2° 2-theta/s.

Thin sections for petrographic analysis were prepared for thirty samples. Thin sections were used to identify minerals, and estimate the proportions of minerals, matrix, and porosity.

RESULTS

Field exposures of the Memphis Sand outcrops can be divided into four typical facies: 1.) massive sands, 2.) cross-bedded or laminated sands, 3.) massive sands with clay intraclasts, and 4.) massive clay and silty clay beds (Figure 9). Outcrop scale features include cross-bedding, cut and fill structures, and bank collapse features. Planar cross beds are commonly found in the informal upper member. Bank collapse features found in outcrops include brecciated clay intraclasts that range from 1.0 to about 20 cm in diameter.

Disconformably overlying the Memphis Sand is a less than 2.0 m thick gravelly sand layer (Figure 9a and 9b). Although it retains no preserved terrace morphology, its lithology, location overlying the Memphis Sand in various geomorphic positions, and presence at most Memphis Sand outcrops is consistent with terrace deposition. The terrace deposit is observed at elevations between 80 and 90 meters above sea level. This terrace gravel is characterized as a moderately consolidated, massive red, reddish yellow, or yellowish red

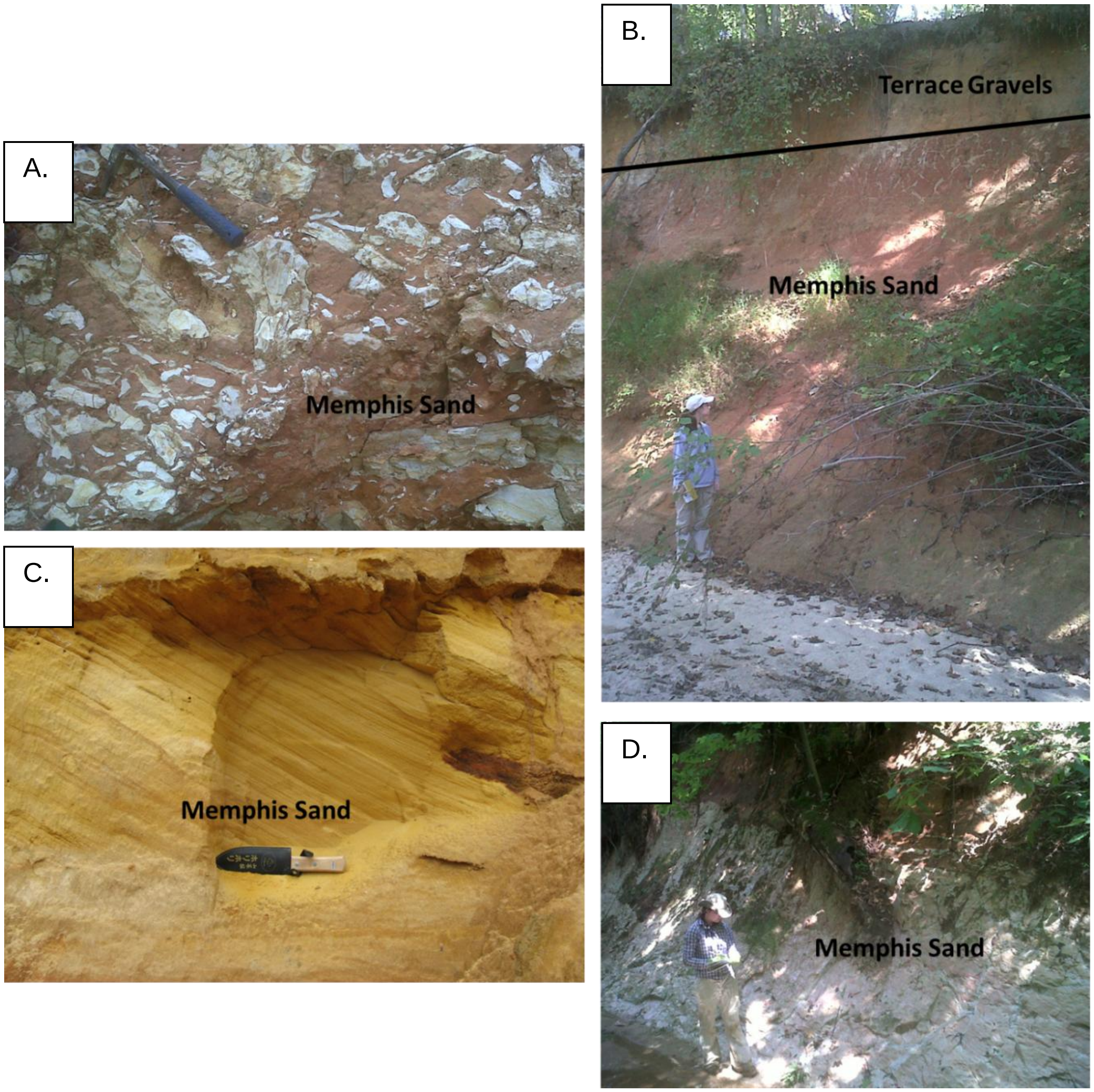


Figure 9. Photos of Memphis Sand and overlying terrace deposits. A. Red, weathered sand with 1 cm to 20 cm white silty clay intraclasts; upper part Memphis Sand. Intraclasts contain ancient root traces and are interpreted to be part of fluvial channel-bank collapse breccia. B. Massive outcrop of Memphis Sand with the overlying terrace deposits; upper Memphis Sand. C. Exposure of planar cross-bedded Memphis Sand, upper Memphis Sand. D. > 1m thick silty clay facies, middle Memphis Sand.

quartz sand with chert pebbles and common iron-oxide concretions. Sands in this layer tend to be fine to coarse, poorly sorted and angular to subrounded. Common silty yellowish brown root traces are present at most locations. Massive sand exposures (Figure 9b) are found more commonly in the Moscow SE quadrangle in the middle and lower part of the Memphis Sand. The sand is semi-consolidated and reddish yellow, yellowish red, red, reddish brown, or very pale brown with rare yellowish red or pinkish white mottling. Grains are fine to medium or fine to coarse, poorly to moderately sorted, spherical or elongated, rounded to angular, unconsolidated quartz. Iron-oxide concretions are present in a few locations as are root traces comprising of both modern varieties filled with yellowish gray silt (reworked loess) and/or ancient traces filled with white clay.

Cross-bedded and laminated sands (Figure 9c) are found more commonly in the Macon quadrangle in the upper part of the Memphis Sand. The sands are unconsolidated to semi-consolidated and red, reddish yellow, pink, or light gray with common white, pale brown, strong brown, or reddish yellow mottling. Grains are fine to medium, fine to coarse, or medium to coarse; well, moderately, or poorly sorted; equant or elongated; subangular to angular; quartz sands.

Massive sands with clay intraclasts (Figure 9a) have red or reddish yellow unconsolidated to semi-consolidated sand with white clay intraclasts. Sands are fine to medium, moderately or well sorted, with spherical, rounded to angular quartz grains. Clay intraclasts are white, medium pebble to small cobble sized, and subangular to angular.

One to greater than two meter thick massive semi-consolidated clay and silty clay beds (Figure 9d) are found in the southern part of the Macon quadrangle and northern two-thirds of the Moscow SE quadrangle within the middle part of the Memphis Sand. The clay beds are white, pale yellow, or light gray with pink, yellow, yellowish brown, or light reddish brown to dark red mottles. Most of the silty clay beds overlie or underlie beds of fine to medium grained sand. Root traces in the clay beds are differentiated by their texture and color.

Two distinct paleosols are developed on the Memphis Sand outcrops (Figure 10). The paleosols are best observed on exposed slope faces of stream valley walls and gullies. Below the modern soil developed in the loess deposits, a thin paleosol is developed on the terrace deposits and then another similar, but thicker paleosol developed in the Memphis Sand. Modern soils in the area are formed in loess and are weakly developed silt loams (Flowers, 1964). The younger paleosol is a well-developed sandy loam to sandy clay loam with accumulation of clay and iron hydroxides in the B horizons and pervasive mottling attributed to roots and root traces. The older paleosol is well-developed and grades from a loamy sand to sand with accumulation of clays and iron oxides in the B horizons and mottling due to ancient root traces. Table 1 shows the amount of iron oxide removed by dithionite citrate treatment performed on the soil samples. More iron oxide was removed from the younger paleosol, but less was removed from the lower paleosol despite its redder color. This could indicate that the younger paleosol, being less developed has weaker iron oxides

Depth (cm)	Horizon	Description
0	A	Some mottling, moderately developed fine to medium subangular blocky structure, silty loam, abundant modern roots
43	A/C	Slightly mottled, moderately developed fine to medium angular blocky structure, loam, abundant modern roots and root traces
193	$2B_{wb}$	Mottled, poorly developed medium to coarse angular blocky structure, less than 10% gravel, loamy sand, with some modern root traces
234	$2B_{tb}$	Very mottled, moderately developed very fine to fine angular blocky structure, abundant clay, sandy clay loam, ancient root traces
249	$3B_{wb2}$	Mottled, poorly developed medium to coarse angular blocky structure, abundant clay clasts, loamy sand, ancient root traces
272	$3B_{tb2}$	Mottled, poorly developed medium to coarse angular blocky, some clay clasts, loamy sand, ancient root traces
320	$3C_{b2}$	Mottled, poorly developed fine to medium subangular blocky structure, some clay clasts, sand

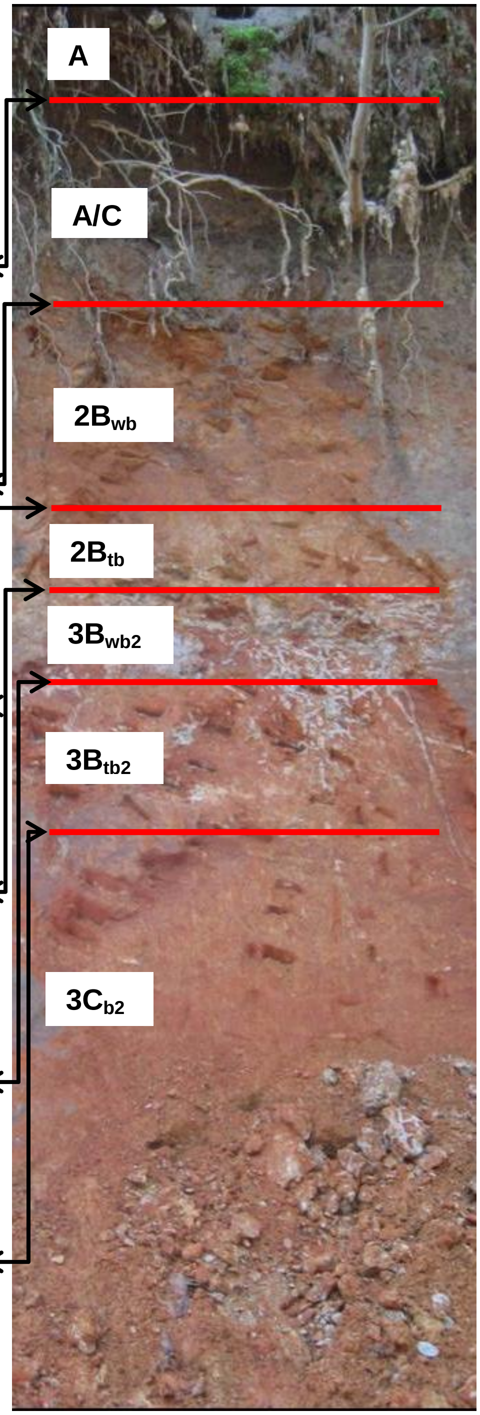


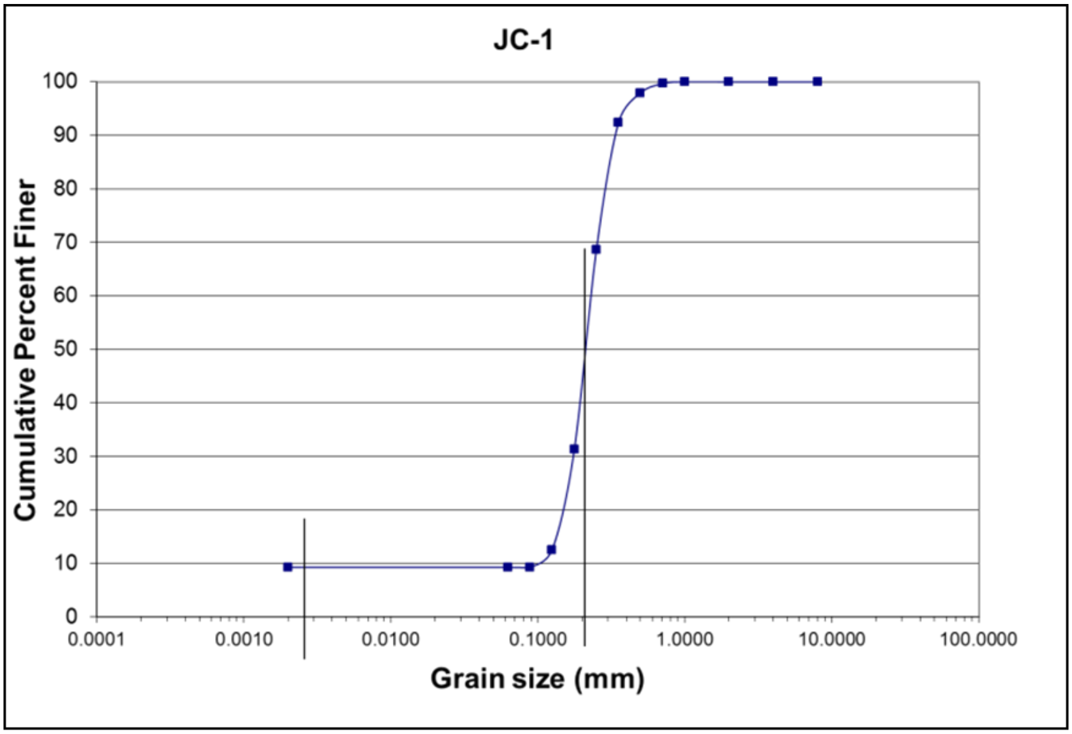
Figure 10. A soil profile created from a Memphis Sand outcrop along Price Rd outside of Williston, TN. The profile includes the modern soil, the younger paleosol developed on the terrace deposits, and the older paleosol developed on the Memphis Sand.

Table 1. Compares the soluble Fe percentages from the Dithionite Citrate removal process performed on the two paleosols with relation to depth. The younger paleosol developed on the terrace deposits is italicized.

Depth (cm)	**Soluble Fe %**
0-43	NA
43-193	NA
193-234	*0.93*
234-249	*0.52*
249-272	0.37
272-320	0.14
320-424	0.10

such as goethite and limonite, whereas the older paleosol has more hematite. Better developed iron oxides such as hematite are more resistant to the removal process, but weaker developed iron oxides such as goethite or limonite are easier to remove (Larsen, personal communication). The boundary between the modern soil and younger paleosol is gradational or abrupt with common silty yellowish gray root traces that help to delineate the boundary. The boundary between the two paleosols is usually abrupt with distinct color and textural changes and pronounced root traces that include both modern yellowish gray silty clay and ancient gray or white silty clay or clay.

Grain size data were plotted using cumulative plots to determine depositional characteristics of the sands. Descriptive statistics from the grain size analysis are presented in Table 2. Because the fines in these samples are primarily post depositional clays, plots were created excluding the fines for better statistical analysis of the sands. Figures 11a and 11b show sample JC-1 (with and without fine fraction), which is from the terrace deposits. Figure 12a and 12b show sample JN-8 which are typical plots of the upper Memphis Sand. Plots of the upper Memphis Sand samples show between 5 and 15 % fines with one outlier, JC-6, that has greater than 30 % fines due to secondary clays from paleosol development. Figures 13a and 13b show sample CR-1 which is typical plot of the middle Memphis Sand. Plots of middle Memphis Sand samples have between 2 and 20 % fines. Figures 14a and 14b show sample BCT-1 which is typical of the upper portion of the lower Memphis Sand. Plots of samples in the lower Memphis Sand have between 5 and 20 % fines with samples BN-1 and BN-2 being outliers with approximately 28 and 42 % fines, respectively. BN-1 and BN-2 show large amounts of secondary clay from paleosol development. Table 2 shows the median, mean, standard deviation, and skewness of the particle size data for each sample with and without fines. All samples with the fines included display a positive skewness because of the inclusion of secondary clays. Without the fines, samples from the upper Memphis Sand show strong fine, fine, and coarse skewness with the majority having a strong fine skewness; samples from the middle Memphis Sand show strong fine, near symmetrical, and strong coarse skewness with half having a strong fine skewness; samples from



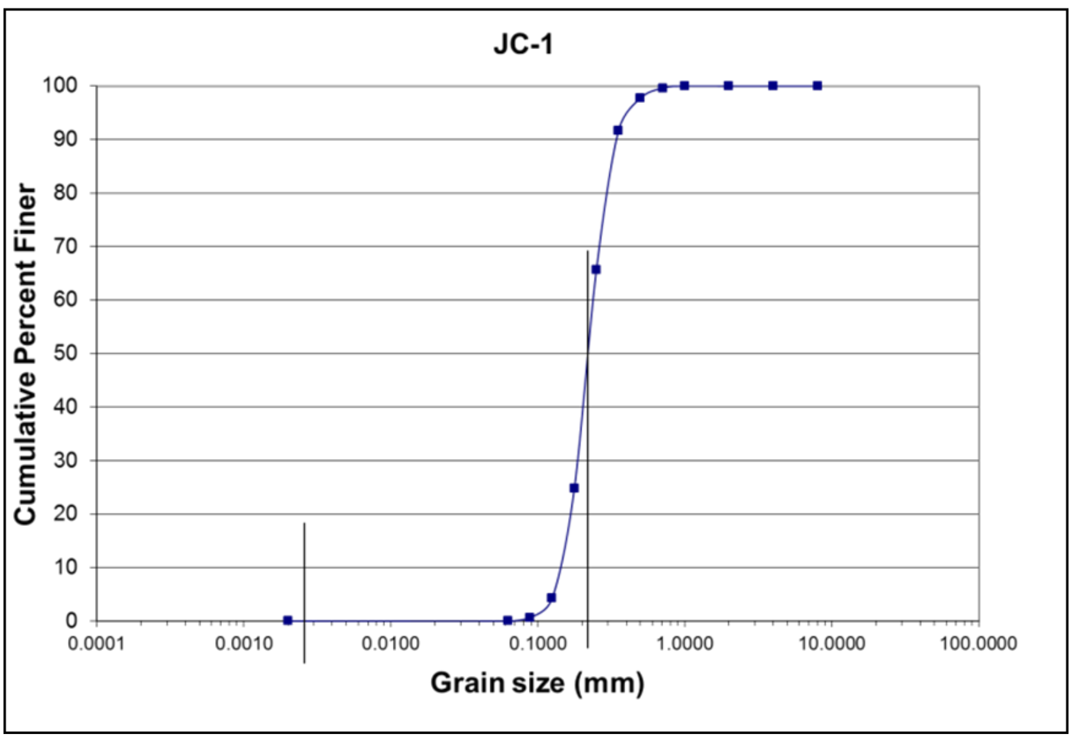
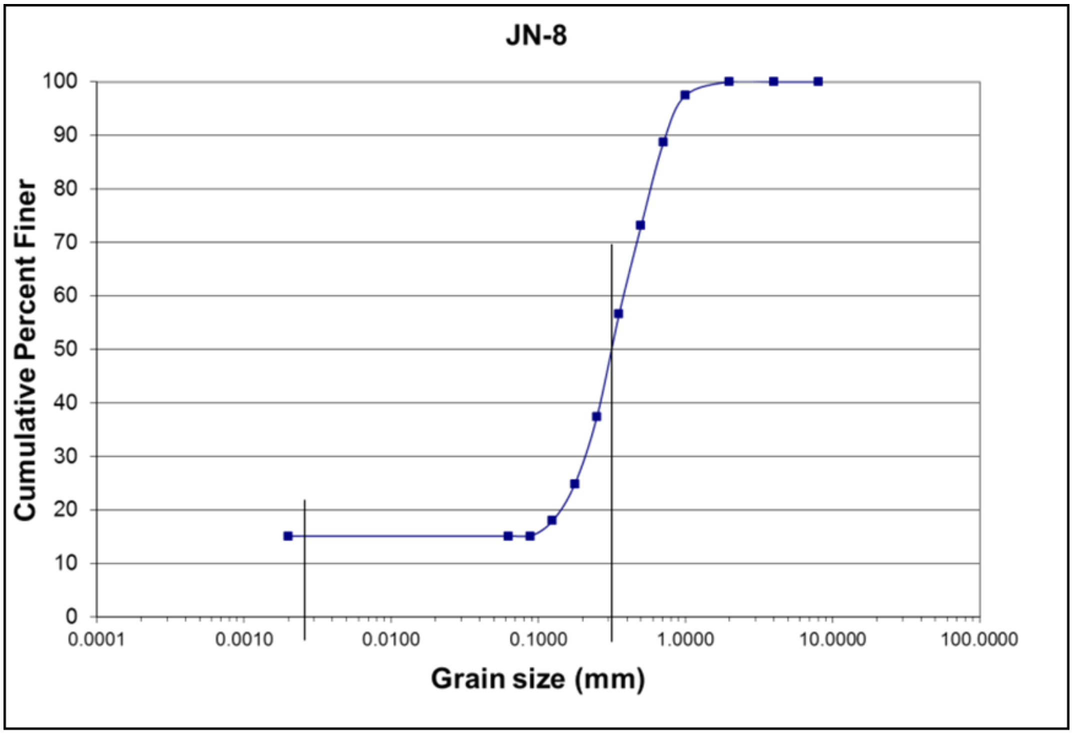


Figure 11. Cumulative plots of the grain size data for sample JC-1, a sample representative of the terrace deposits. A. JC-1 with the fine fraction included. B. JC-1 without the fine fraction included. Vertical lines on the graphs indicate the lower sand fraction boundary and the median particle size.



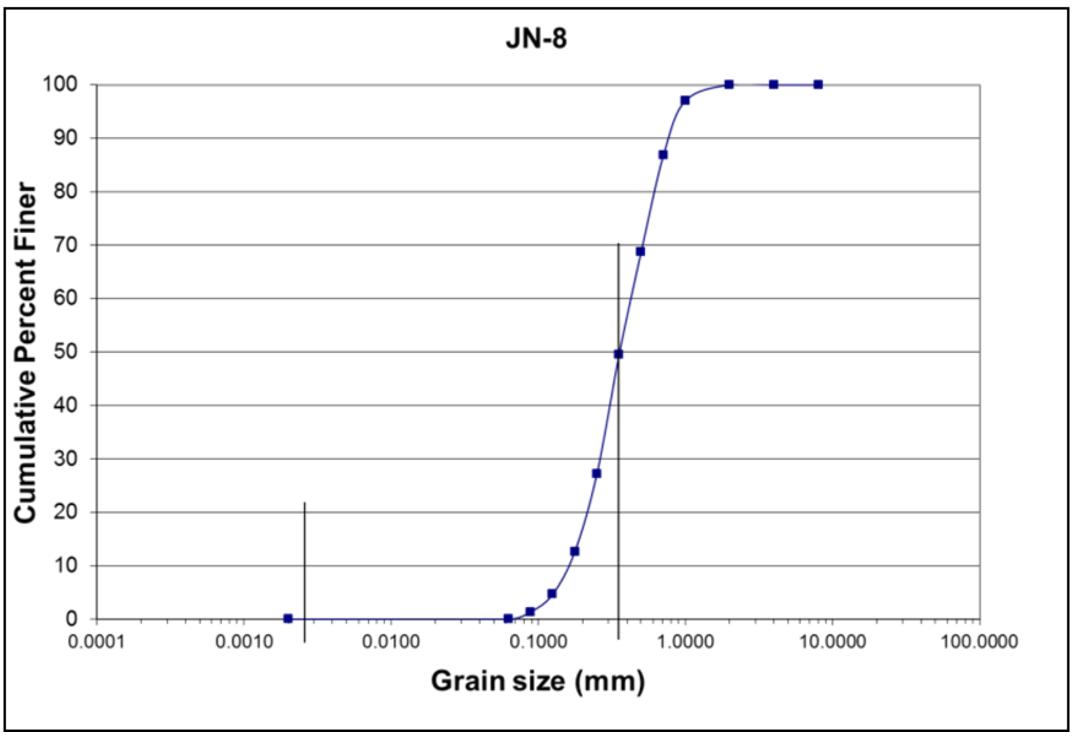


Figure 12. Cumulative plots of the grain size data for sample JN-8, a sample representative of the upper Memphis Sand informal member. A. JN-8 with the fine fraction included. B. JN-8 without the fine fraction included. Vertical lines on the graphs indicate the lower sand fraction boundary and the median particle size.

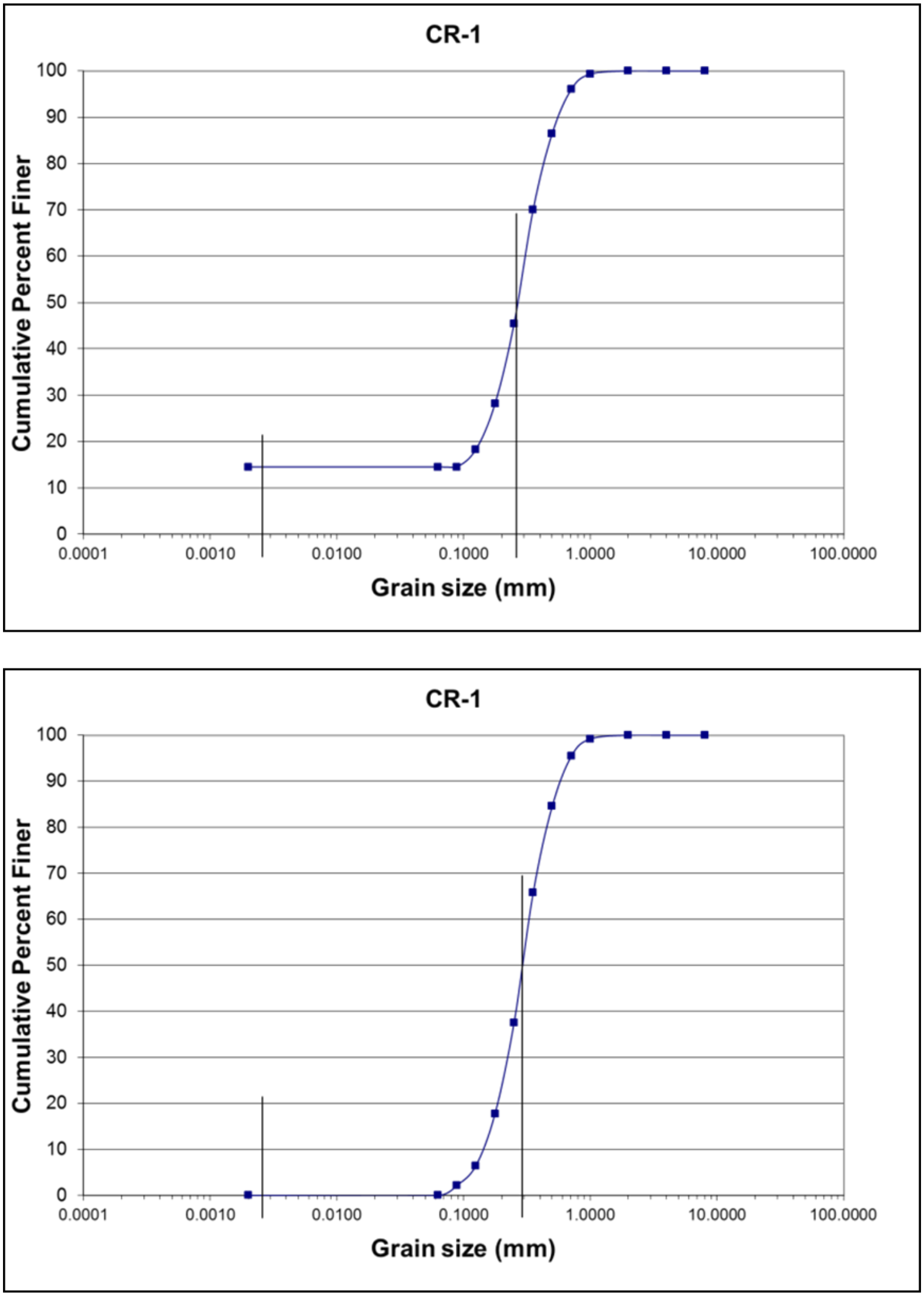


Figure 13. Cumulative plots of the grain size data for sample CR-1, a sample representative of the middle Memphis Sand informal member. A. CR-1 with the fine fraction included. B. CR-1 without the fine fraction included. Vertical lines on the graphs indicate the lower sand fraction boundary and the median particle size.

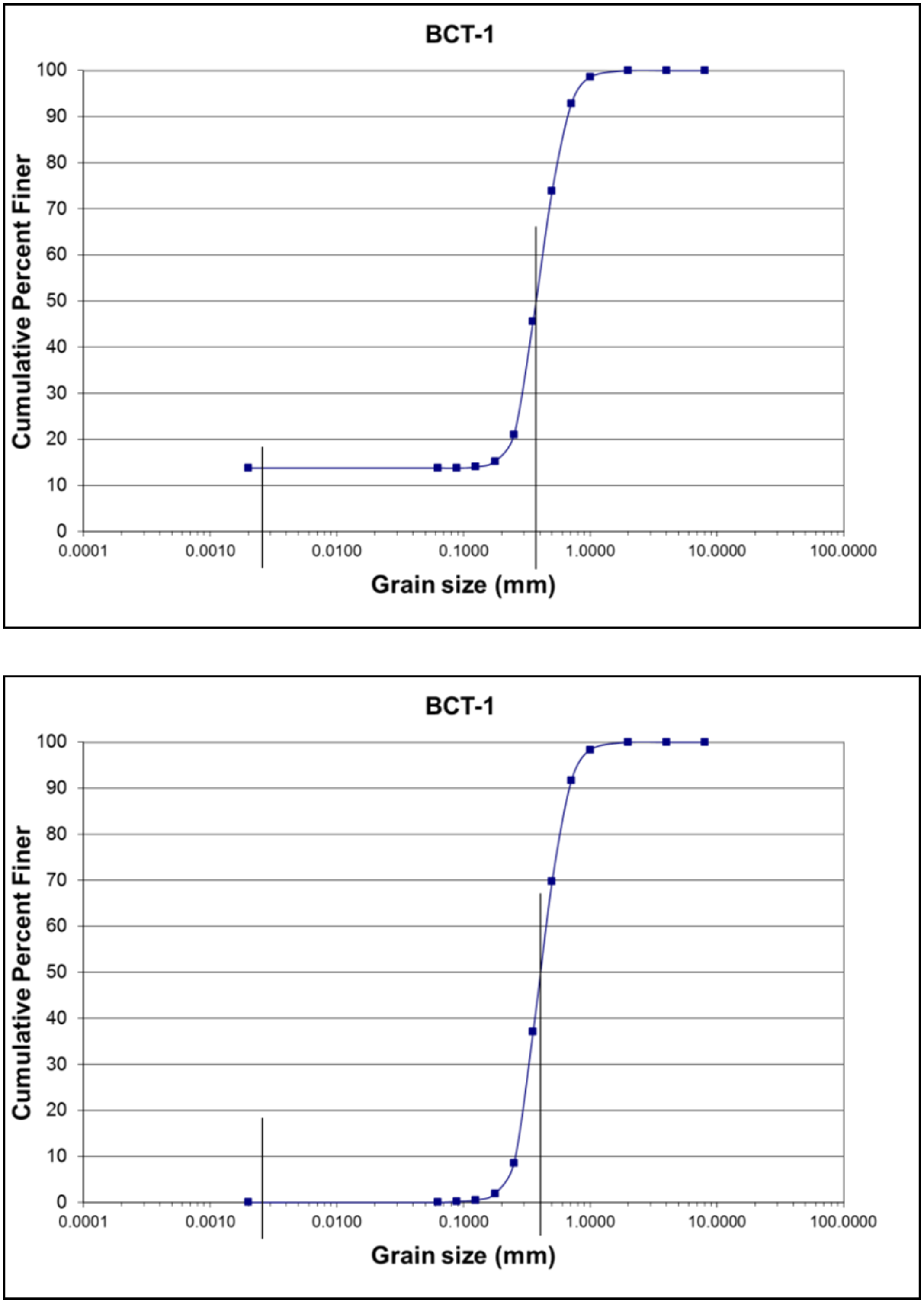


Figure 14. Cumulative plots of the grain size data for sample BCT-1, a sample representative of the lower Memphis Sand informal member. A. BCT-1 with the fine fraction included. B. BCT-1 without the fine fraction included. Vertical lines on the graphs indicate the lower sand fraction boundary and the median particle size.

Table 2. Statistical data for all the grain size data with and without the fine fraction for each sample including the median, mean, standard deviation, and skewness. The associated terrace deposits are italicized.

Table 2. Particle Size Statistical Data

	With Fine Fraction (>4.0Φ)				Without Fine Fraction (>4.0Φ)			
Sample ID	Median Φ	Mean Φ	Standard Deviation σ	Skewness	Median Φ	Mean Φ	Standard Deviation σ	Skewness
WR-1	1.79	2.21	1.30	4.25	1.79	1.96	0.39	1.47
WR-2	1.96	2.59	1.90	2.64	1.89	2.01	0.42	0.45
JC-1	*2.25*	*2.75*	*1.90*	*2.46*	*2.18*	*2.17*	*0.53*	*-0.25*
JC-2	*2.74*	*3.59*	*2.14*	*1.72*	*2.64*	*2.71*	*0.54*	*-0.02*
JC-6	2.64	4.30	2.90	0.68	2.32	2.38	0.68	-0.29
JC-8	1.64	2.53	2.63	1.58	1.47	1.48	0.88	0.11
CC-2	1.47	2.15	2.17	2.33	1.64	1.48	0.70	1.62
ST-1	1.64	2.12	1.94	2.79	1.32	1.57	0.48	0.48
AP-1	*1.64*	*1.93*	*3.09*	*0.91*	*1.32*	*0.88*	*1.74*	*-0.67*
HC-1	0.84	1.49	2.85	1.68	0.51	0.49	1.12	-0.07
KFG-1	2.40	2.56	1.42	2.76	-0.06	-0.10	0.99	1.80
CR-1	1.89	2.75	2.46	1.67	2.12	2.09	0.49	0.77
PR-1	1.40	2.44	2.68	1.71	2.25	2.25	0.61	-2.22
ZK-1	-0.36	0.51	2.41	2.58	1.32	1.33	0.86	-0.12
ZK-3	2.06	2.33	1.33	3.85	1.47	1.48	0.92	-0.04
ZK-4	2.32	3.22	2.33	1.64	1.51	1.50	0.58	-0.21
BN-1	1.74	3.36	3.31	0.80	1.74	1.79	0.79	0.05
BN-2	2.47	4.48	3.54	0.18	1.29	1.31	0.61	0.42
PWXW-1	1.60	2.27	2.26	2.22	2.47	2.45	0.70	-0.25
LRC-1	2.64	3.59	2.44	1.35	1.32	1.29	0.60	-0.08
BCT-1	1.40	2.28	2.54	1.90	2.40	2.31	0.76	-0.05

the lower Memphis Sand show strong fine, near symmetrical, and coarse skewness with the majority having a near symmetrical skewness. Samples in the upper and middle Memphis Sand tend to be more fine grained, and samples in the lower Memphis Sand tend to be slightly more coarse grained. Plots of samples of the terrace deposits have between 9 and 17 % fines. Figures 11a and 11b show sample JC-1, which is representative coarse grained. Samples from the terrace deposits show near symmetrical, coarse, and strong coarse skewness indicating that these samples are mostly coarse grained. The standard deviation of Phi provides a quantitative measure of sorting of sediments. Samples, without the fines included, of the upper Memphis Sand are moderately to well sorted. Samples of the middle Memphis Sand are poor to well sorted. Samples of the lower Memphis Sand are moderately or moderately well sorted. Samples of the reworked terrace gravel are either poor or moderately well sorted.

Thin section characteristics such as whole rock percentage, grain type, quartz type, porosity type, cement type, and matrix type for each sample are tabulated in Table 3. Most of the thin sections are primarily composed of both monocrystalline and polycrystalline quartz. Quartz grains range from very fine to coarse grained, and are poorly to well sorted and angular to rounded (Figure 15a). Most grains are equant or elongated. Some monocrysalline quartz grains are cloudy, have inclusions, or are gouged into crescentic or highly angular pieces. Most monocrystalline quartz is subangular to angular. Polycrystalline quartz is mostly subangular to rounded and less commonly present in clusters

Table 3. Table showing detailed thin section descriptions of each sample. Terrace gravels have an asterisk by the sample name.

Table 3. Petrologic Analysis of Thin Sections																		
Sample ID	**Whole Rock %**				**Grain Type**					**Quartz**								**Notes**
	Grains	Matrix	Pore	Cement	Quartz	Feldspar	Rock Fragments	Mica	Other	Monocrystalline Quartz	Polycrystalline Quartz	Primary Porosity	Secondary Porosity	Clay cement	FeOx cement	Primary Matrix	Secondary Matrix	
Dog-1a	60	20	20	0	100	0	0	0	0	100	0	100	0	100	0	0	100	Accessory minerals include muscovite, kyanite, zircon, biotite, rutile
Dog-1b*	65	10	25	0	100	0	0	0	0	98	2	100	0	100	0	0	100	Accessory minerals include muscovite, zircon, kyanite, biotite, rutile, tourmaline, and horneblende
OWC-1a	2	98	0	0	95	0	0	5	0	100	0	100	0	100	0	95	5	Accessory minerals include muscovite, zircon, kyanite, rutile, and biotite.

Table 3. Petrologic Analysis of Thin Sections

Sample ID	Whole Rock %				Grain Type					Quartz								Notes
	Grains	Matrix	Pore	Cement	Quartz	Feldspar	Rock Fragments	Mica	Other	Monocrystalline Quartz	Polycrystalline Quartz	Primary Porosity	Secondary Porosity	Clay cement	FeOx cement	Primary Matrix	Secondary Matrix	
OWC-1b	70	5	25	0	100	0	0	0	0	95	5	100	0	100	0	0	100	Accessory minerals include muscovite, zircon, kyanite, and rutile.
WR-1	60	0	40	0	100	0	0	0	0	90	10	100	0	90	10	0	100	Accessory minerals include kyanite, zircon, muscovite, sillamanite, and rutile.
WR-2	65	5	30	0	100	0	0	0	0	95	5	100	0	70	30	0	100	Accessory minerals include muscovite, kyanite, zircon, rutile, and biotite.

Table 3. Petrologic Analysis of Thin Sections

Sample ID	Whole Rock %				Grain Type					Quartz								Notes
	Grains	Matrix	Pore	Cement	Quartz	Feldspar	Rock Fragments	Mica	Other	Monocrystalline Quartz	Polycrystalline Quartz	Primary Porosity	Secondary Porosity	Clay cement	FeOx cement	Primary Matrix	Secondary Matrix	
WR-3	35	55	10	0	100	0	0	0	0	100	0	100	0	100	0	80	20	Accessory minerals include muscovite, zircon, kyanite, rutile, and biotite.
JC-5*	70	25	5	0	100	0	0	0	0	95	5	100	0	95	5	0	100	Accessory minerals include zircon, kyanite, rutile, and sillamanite.
JC-6	60	20	20	0	100	0	0	0	0	98	2	100	0	100	0	0	100	Accessory minerals include zircon, muscovite, rutile, kyanite, biotite, and sillimanite.

Table 3. Petrologic Analysis of Thin Sections

Sample ID	Whole Rock %				Grain Type					Quartz								Notes
	Grains	Matrix	Pore	Cement	Quartz	Feldspar	Rock Fragments	Mica	Other	Monocrystalline Quartz	Polycrystalline Quartz	Primary Porosity	Secondary Porosity	Clay cement	FeOx cement	Primary Matrix	Secondary Matrix	
JC-7a	40	50	10	0	100	0	0	0	0	100	0	100	0	100	0	0	100	Accessory minerals include rutile, kyanite, and zircon.
JC-7b	60	35	15	0	100	0	0	0	0	95	5	100	0	100	0	0	100	Accessory minerals include zircon, kyanite, and rutile.
CC-1	65	5	30	0	100	0	0	0	0	95	5	100	0	100	0	0	100	Accessory minerals include zircon, muscovite, biotite, rutile, and kyanite.
CC-2a	70	10	20	0	100	0	0	0	0	90	10	100	0	100	0	0	100	Accessory minerals include zircon, muscovite, kyanite, and biotite.

Table 3. Petrologic Analysis of Thin Sections

Sample ID	Whole Rock %				Grain Type					Quartz								Notes
	Grains	Matrix	Pore	Cement	Quartz	Feldspar	Rock Fragments	Mica	Other	Monocrystalline Quartz	Polycrystalline Quartz	Primary Porosity	Secondary Porosity	Clay cement	FeOx cement	Primary Matrix	Secondary Matrix	
CC-2b	75	5	20	0	100	0	0	0	0	95	5	100	0	100	0	0	100	Accessory minerals include zircon, kyanite, muscovite, biotite, and rutile.
ST-1	60	5	35	0	100	0	0	0	0	85	15	100	0	100	0	0	100	Accessory minerals include kyanite, zircon, and muscovite.
AP-2	30	70	0	0	100	0	0	0	0	N/A	N/A	100	0	100	0	100	0	Accessory minerals include muscovite and zircon.
AL-1	45	50	5	0	100	0	0	0	0	N/A	N/A	100	0	80	20	100	0	Accessory minerals include muscovite.

Table 3. Petrologic Analysis of Thin Sections

Sample ID	Whole Rock %				Grain Type					Quartz								Notes
	Grains	Matrix	Pore	Cement	Quartz	Feldspar	Rock Fragments	Mica	Other	Monocrystalline Quartz	Polycrystalline Quartz	Primary Porosity	Secondary Porosity	Clay cement	FeOx cement	Primary Matrix	Secondary Matrix	
HC-1	70	10	20	0	100	0	0	0	0	50	50	100	0	100	0	0	100	Accessory minerals include kyanite and muscovite.
CR-1	70	10	20	0	100	0	0	0	0	95	5	100	0	100	0	0	100	Accessory minerals include kyanite and zircon.
PR-1	65	15	20	0	100	0	0	0	0	95	5	100	0	100	0	0	100	Accessory minerals include kyanite.
KFG-1	75	5	20	0	100	0	0	0	0	95	5	100	0	100	0	0	100	Accessory minerals include muscovite, kyanite, biotite, and zircon.

Table 3. Petrologic Analysis of Thin Sections

Sample ID	Whole Rock %				Grain Type					Quartz								Notes
	Grains	Matrix	Pore	Cement	Quartz	Feldspar	Rock Fragments	Mica	Other	Monocrystalline Quartz	Polycrystalline Quartz	Primary Porosity	Secondary Porosity	Clay cement	FeOx cement	Primary Matrix	Secondary Matrix	
ZK-2	35	60	5	0	95	0	0	5	0	N/A	N/A	100	0	100	0	100	0	Accessory minerals include kyanite, muscovite, and biotite.
ZK-3	55	0	45	0	100	0	0	0	0	95	5	100	0	100	0	0	100	Accessory minerals include kyanite, muscovite, biotite, and zircon.
ZK-4	60	10	30	0	100	0	0	0	0	95	5	100	0	100	0	0	100	Accessory minerals include muscovite, zircon, and kyanite.
BN-1	60	30	10	0	100	0	0	0	0	95	5	100	0	100	0	0	100	Accessory minerals include muscovite and kyanite.

Table 3. Petrologic Analysis of Thin Sections

Sample ID	Whole Rock %				Grain Type					Quartz								Notes
	Grains	Matrix	Pore	Cement	Quartz	Feldspar	Rock Fragments	Mica	Other	Monocrystalline Quartz	Polycrystalline Quartz	Primary Porosity	Secondary Porosity	Clay cement	FeOx cement	Primary Matrix	Secondary Matrix	
BN-2	55	35	10	0	100	0	0	0	0	95	5	100	0	100	0	0	100	Accessory minerals include muscovite and kyanite.
PWX-1	65	15	20	0	100	0	0	0	0	90	10	100	0	100	0	0	100	Accessory minerals include kyanite, zircon, and biotite.
LRC-2	55	15	30	0	100	0	0	0	0	98	2	100	0	100	0	100	0	Accessory minerals include muscovite, kyanite, biotite, and zircon.
BCT-1	70	5	25	0	100	0	0	0	0	98	2	100	0	100	0	0	100	Accessory minerals include kyanite, biotite, and rutile.

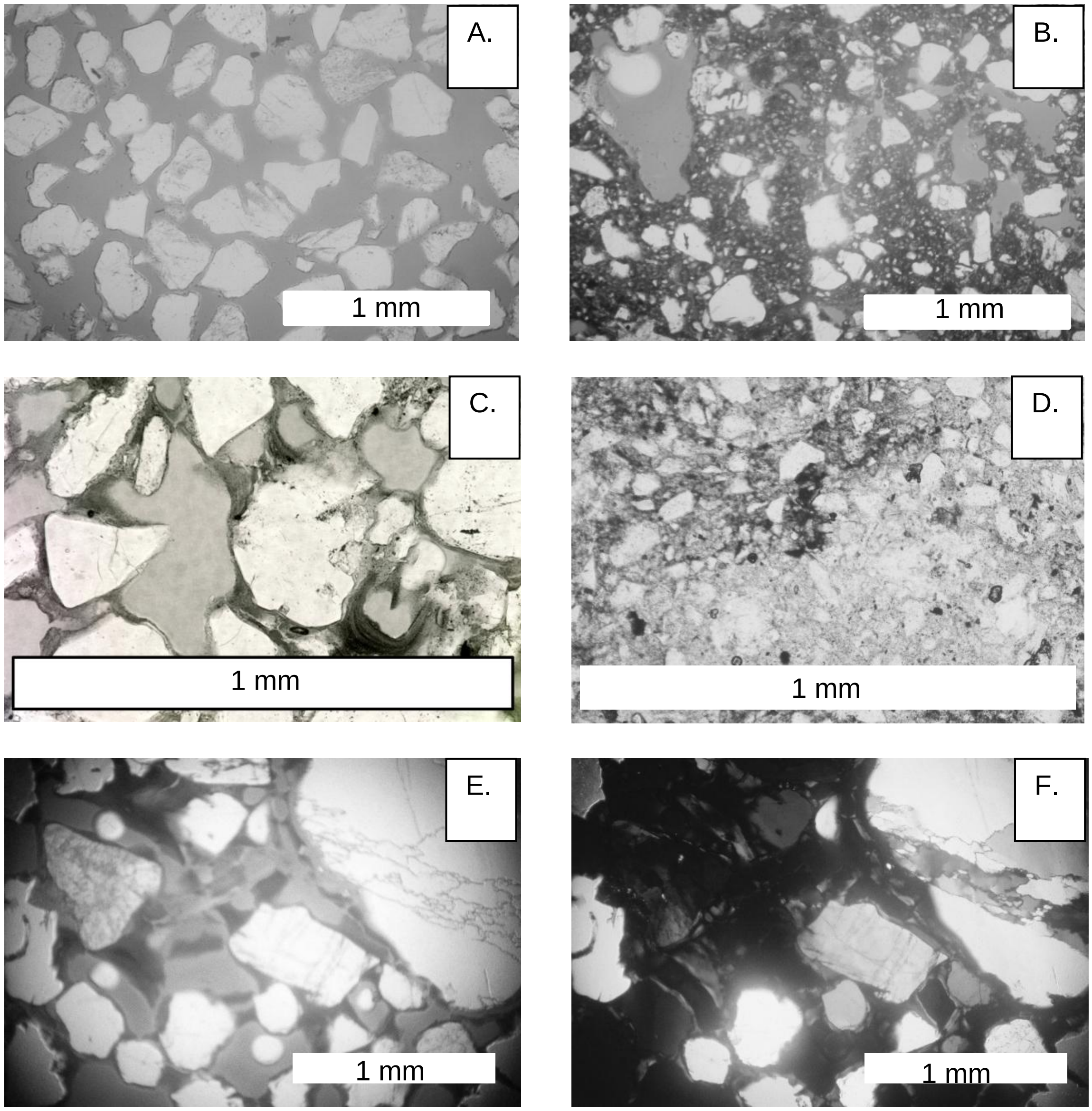


Figure 15. a. Thin section of sample WR-1 (40x, UXN) found in the Macon quadrangle showing a good example of grain angularity and composition. B. Thin section of sample JC-7a (40x, UXN) found in the Macon quadrangle showing a good example of abundant secondary matrix. C. Thin section of sample CR-1 (100x, UXN) in the Moscow SE quadrangle showing a good example of secondary matrix characteristics such as bridges and meniscus boundaries. D. Thin section of sample ZK-2 (100x, UXN) in the Moscow SE quadrangle showing a good example of a silty clay bed. E. Thin section of sample HC-1 (40x, UXN) showing a good example of both monocrystalline quartz and polycrystalline quartz. F. Thin section of sample HC-1 (40x, XN) showing a good example of both monocrystalline quartz and polycrystalline quartz.

(Figure 15e and 15f). Most samples include 5 to 15 % secondary matrix, shown in Figure 15b and 15c. Secondary matrix is identified by its red or brown color, meniscus boundaries, bridges, coatings, and banding (Figure 15c). In some samples (Figure 15b), 25 to 35 % secondary matrix fills most pore space. Iron oxide cement is present in a few samples. Porosity for most samples is 20 % or greater with the exception of samples filled with secondary matrix. Secondary porosity is not observed. A few thin sections are from siltstones with very fine grained sand (Figure 15d). These samples have primary matrix and very fine sand-size grains of quartz. The quartz in these samples is too fine to resolve specific characteristics.

Common accessory minerals in the sands include muscovite, kyanite, and zircon. Rare accessory minerals include biotite and rutile. Very rare accessory minerals include sillimanite, tourmaline, and hornblende. Rock fragments and opaques are also found in most samples. Samples in the middle and lower Memphis Sand have a low diversity accessory mineral assemblage dominated by muscovite and kyanite with rare biotite and zircon. Samples from the upper Memphis Sand contain a greater variety of accessory minerals, including rutile, sillimanite, tourmaline, and hornblende in addition to the previously mentioned accessory minerals.

X-ray Diffraction was performed on 5 samples to determine their clay mineralogy. Four samples, WR-3, AP-1, LRC-1, and KFG-2 are from thick clay or siltstone beds. Sample CC-1 is from clay intraclasts in a predominately sand exposure in a stream bed. Sample WR-3 (Figure 16) shows the strongest peak

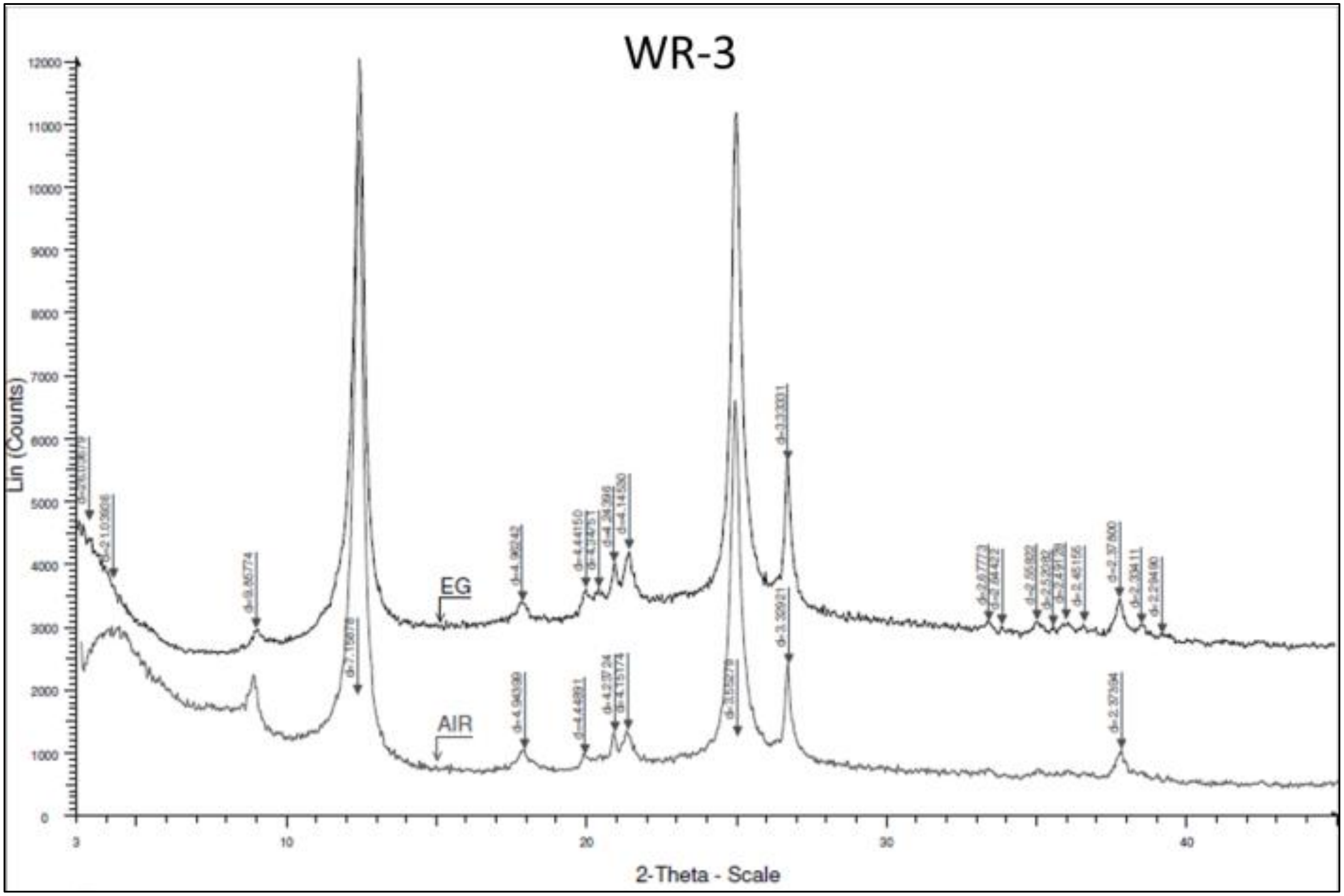


Figure 16. Sample WR-3 is a sample from a clay bed and shows peaks for Kaolinite (d-spacing 7.16, 3.58, and 2.38), Illite (d-spacing 10.1, 5.00, and 3.38), Quartz (d-spacing 4.25), and Cristobalite (d-spacing 4.15 and 2.53).

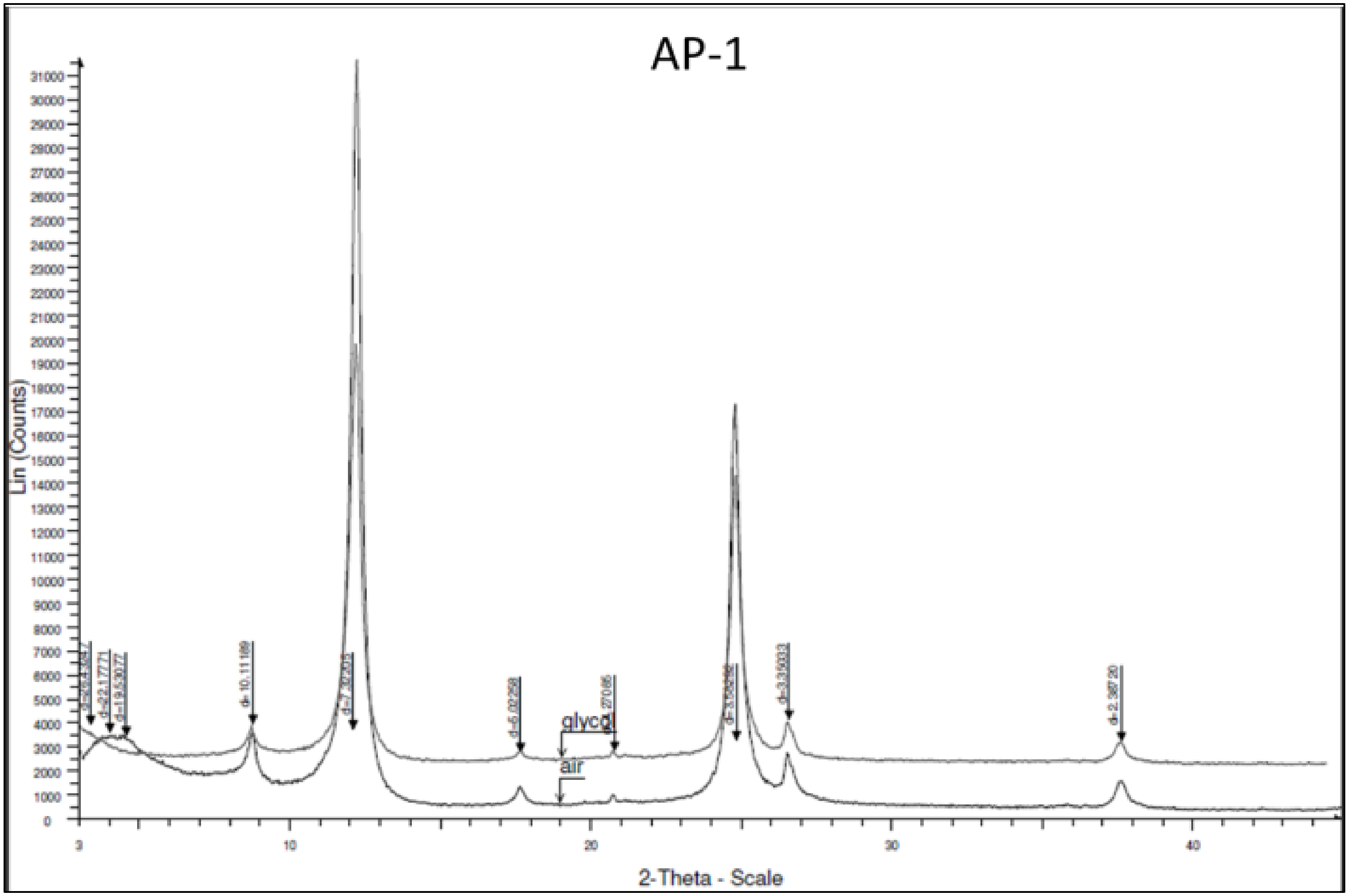


Figure 17. Sample AP-1 is a sample from a clay bed and shows peaks for Kaolinite (d-spacing 7.16, 3.58, and 2.38), Illite (d-spacing 10.1, 5.00, and 3.38), and Quartz (d-spacing 4.25).

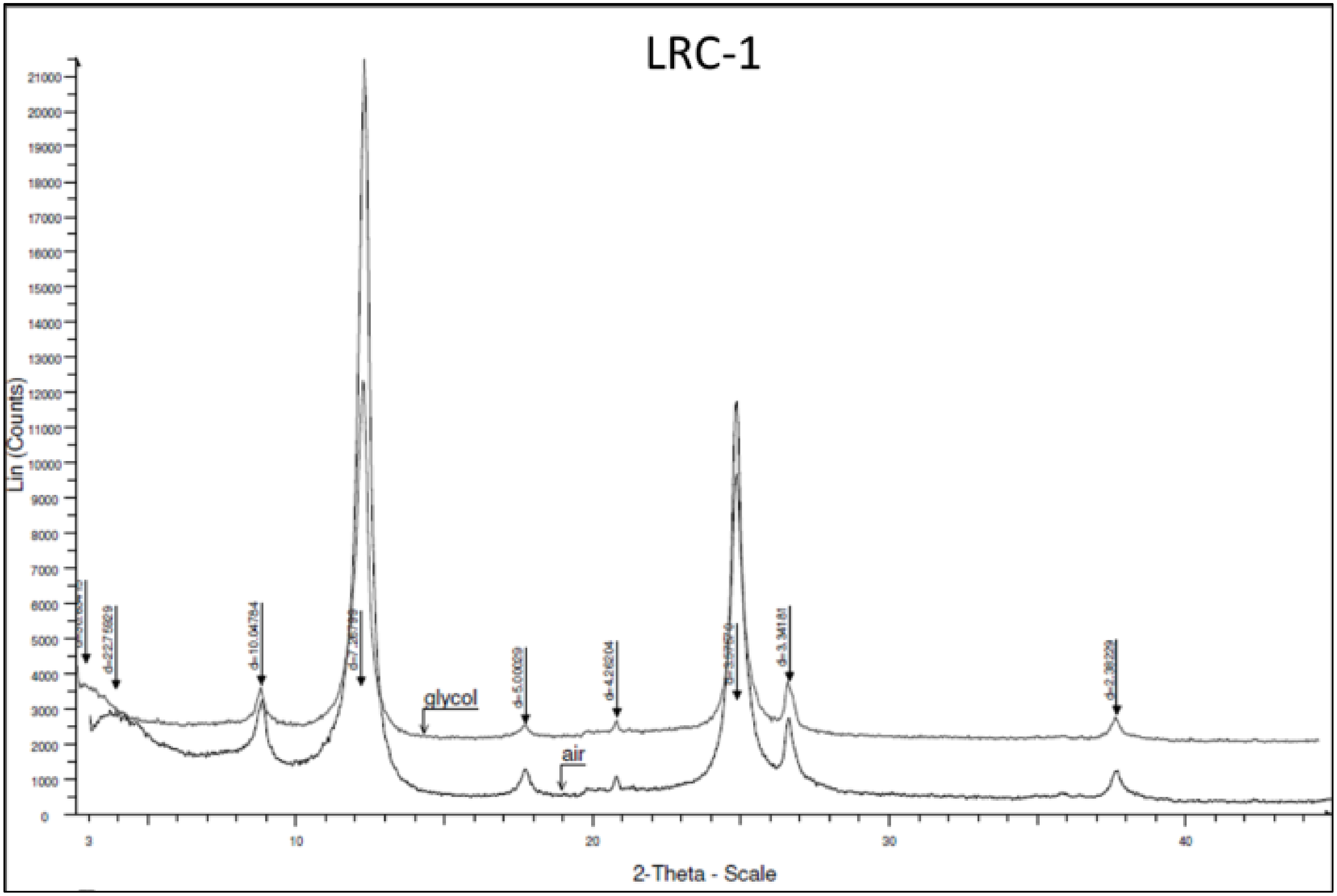


Figure 18. Sample LRC-1 is a sample from a clay bed and shows peaks for Kaolinite (d-spacing 7.16, 3.58, and 2.38), Illite (d-spacing 10.1, 5.00, and 3.38), and Quartz (d-spacing 4.25).

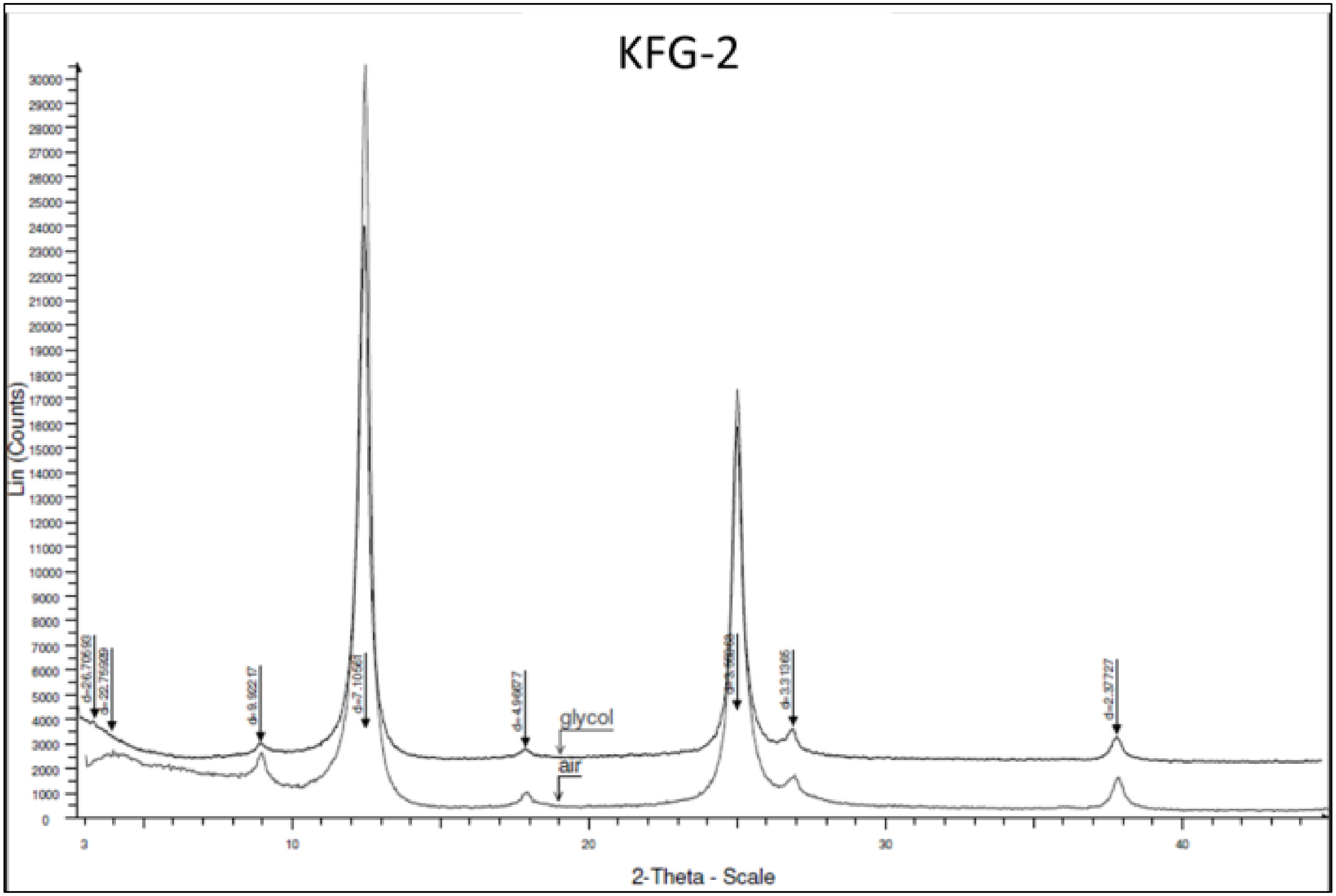


Figure 19. Sample KFG-2 is a sample from a clay bed and shows peaks for Kaolinite (d-spacing 7.16, 3.58, and 2.38) and Illite (d-spacing 10.1, 5.00, and 3.38).

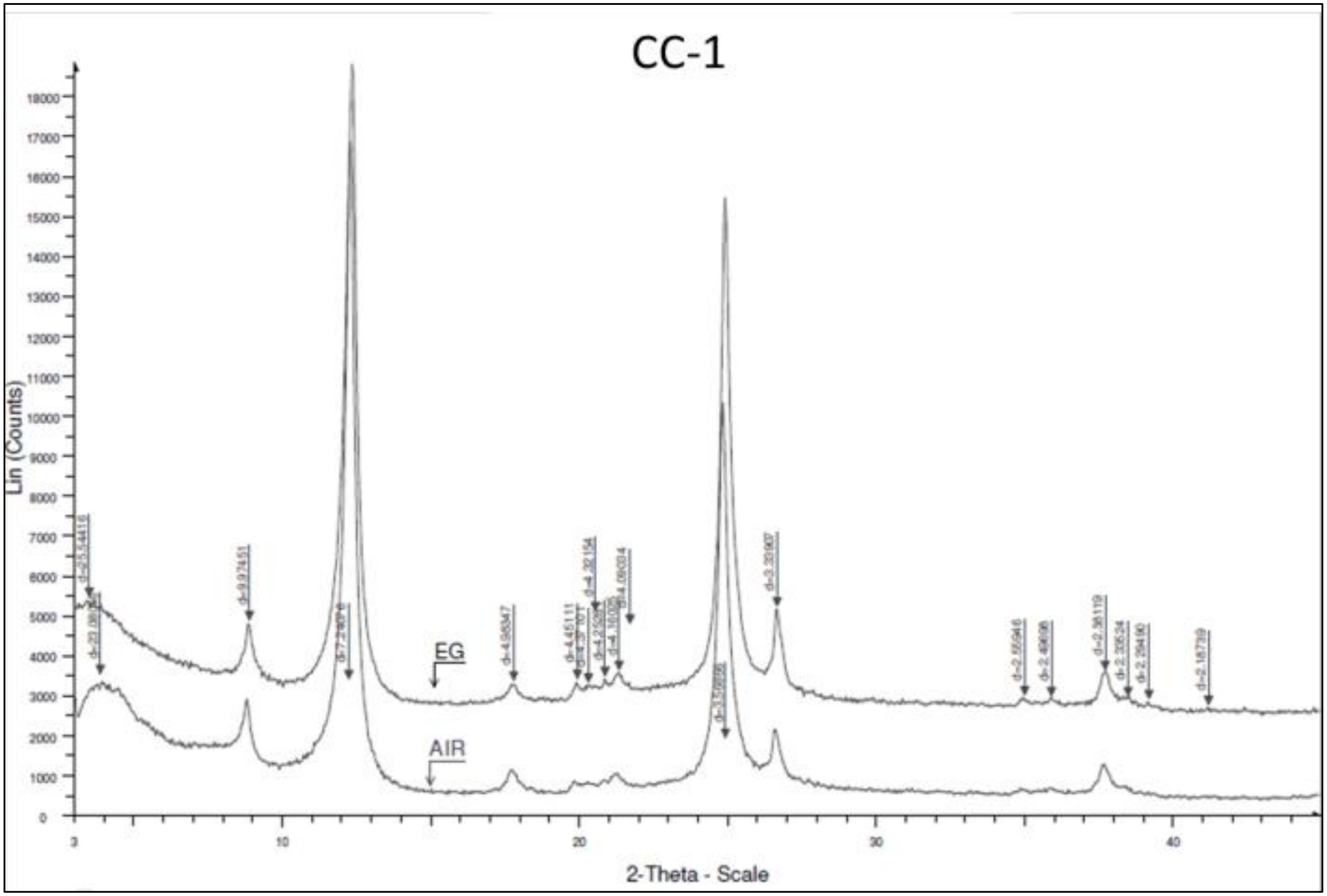


Figure 20. Sample CC-1 is a sample from clay clasts and shows peaks for Kaolinite (d-spacing 7.16, 3.58, and 2.38), Illite (d-spacing 10.1, 5.00, and 3.38), Quartz (d-spacing 4.25), and Cristobalite (d-spacing 4.15 and 2.53).

for kaolinite. It shows a minor peak for illite, and trace peaks for quartz and cristobalite. Sample AP-1 (Figure 17) shows strong peaks for kaolinite, minor peaks for illite, and a trace peak for quartz. Sample LRC-1(Figure 18) shows strong peaks for kaolinite, minor peaks for illite, and a trace peak for quartz. Sample KFG-2 (Figure 19) shows strong peaks for kaolinite and minor peaks for illite. Sample CC1 (Figure 20) shows strong peaks for kaolinite, minor peaks for illite, and trace peaks for quartz and cristobalite. All samples showed a response for expandable clays after solvation with ethylene glycol, which are interpreted as smectite.

DISCUSSION

Memphis Sand Stratigraphy

Varying stratigraphic characteristics found in thin sections and field descriptions support the tripartite division of the Memphis Sand into the upper Memphis Sand, middle Memphis Sand, and lower Memphis Sand (Figure 21). The upper Memphis Sand crops out with similar characteristics over most of the northern two-thirds of the Macon quadrangle. Outcrops in the northern two-thirds of the Macon Quadrangle were predominately laminated or cross bedded pink, reddish yellow or red, fine to coarse, well sorted sands. Some outcrops include iron oxide concretions toward the northern and middle portion of the Macon quad. The upper Memphis Sand can be correlated to the Kosciusko Sands in Mississippi of based on sedimentary structures and colors of sand (Vestal, 1954). In the southern third portion of the Macon quadrangle outcrop characteristics

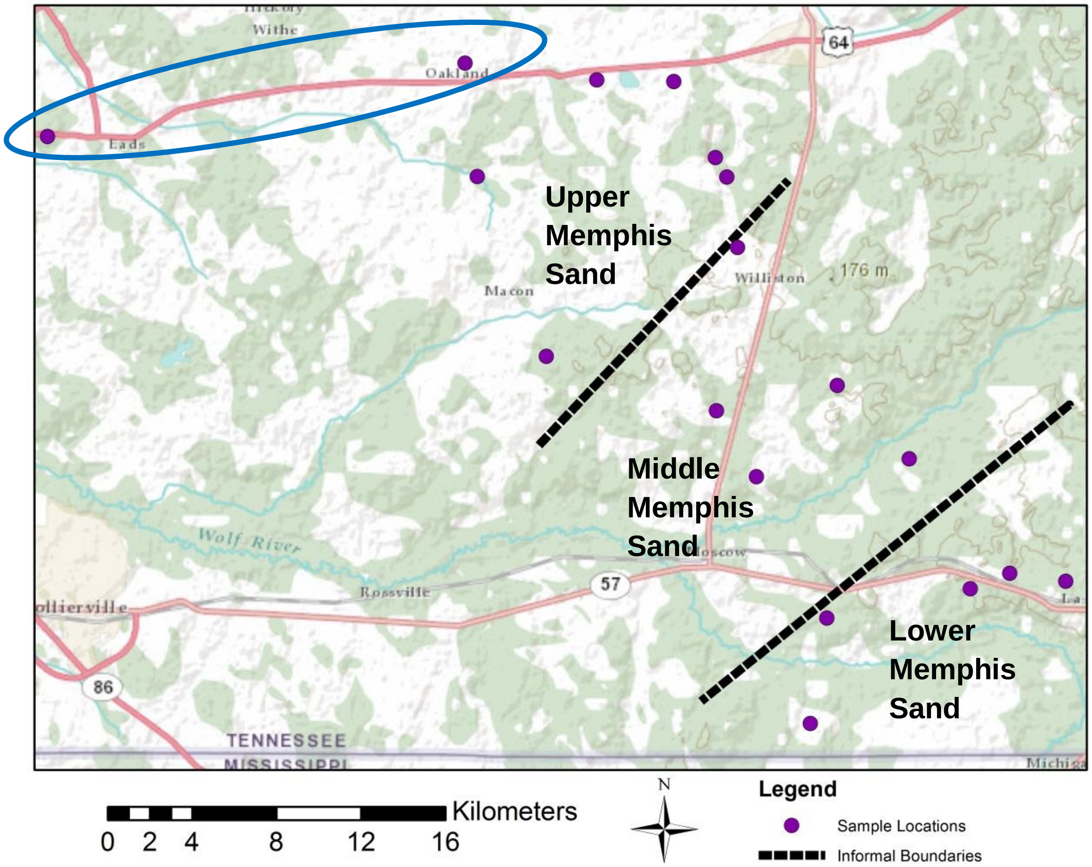


Figure 21. Map of the study area showing the sample locations divided into the upper, middle, and lower Memphis Sand informal members. The circled sample locations are both from the upper Claiborne Group, not the Memphis Sand.

resemble the basal Kosciusko where fine grained micaceous sands overlay thick pink or white silty clay beds (Vestal, 1954).

A thick grayish clay layer is observed in an outcrop slightly south of the Macon quad and slightly west of the Moscow SE quad along Hargis Creek. A similar layer is observed in an outcrop along Allen Rd in the southeastern part of the Macon quadrangle. This layer is consistent with clays and silts correlative to the Zilpha Clay in Mississippi (Waldron et al., 2011). The Zilpha clay is typically defined as a light to dark gray clay that is glauconitic in parts of central Mississippi and further south (Hosman, 1996; Thomas, 1942). No glauconite was found in our samples. This suggests that fluvial processes dominated during Claiborne time in the study area and it was north of marine and transitional zone. In the northern half of the Moscow SE quadrangle, thick silty clay beds are noted along with more micaceous interbedded sands and clays resembling the middle Memphis Sand described by Waldron et al. (2011). The combination of clays, silts, and sands are also characteristic of the Tallahatta formation in Mississippi (Vestal, 1954). Samples across the northern half of the Moscow SE quadrangle are primarily siltstones or fine to coarse massive micaceous sands that are light gray, very pale brown, yellowish red to reddish brown with a variety of mottling. Sands had up to 50% fines in some samples mostly attributed to secondary clays resulting from paleosol development. The Basic City Shale Member is the lowest member of the Tallahatta Formation in Mississippi (Vestal, 1954) and is greenish gray silty clay that is considered the boundary between the middle and lower Memphis Sand (Waldron et al., 2011). Although no direct outcrops of a greenish gray siltstone are found, a consistent white clay interval is observed in the southeastern portion of the Moscow SE quad in the general area where the bottom of the middle Memphis Sand is likely to be exposed and is most likely a northern correlative of the Basic City Shale.

The southern half of the Moscow SE quadrangle contains sands that were much more micaceous fine to coarse massive sands characteristic of the lower Memphis Sand (Hundt, 2008). The lower Memphis Sand is correlative to the Meridian Sand of Mississippi whose characteristics include fine whitish sands to coarser brown and red brown massive to cross bedded sands with some ferruginous sands (Vestal, 1954). Memphis Sand exposures in the SE corner of the Moscow SE quad range from fine to coarse light gray, reddish yellow to reddish brown massive or cross bedded micaceous sands with some oxidized concretions similar to descriptions of outcrops of the Meridian Sands in Marshall County Mississippi (Vestal, 1954).

In summary, characteristics of the upper, middle and lower Memphis Sand correlative to the Kosciusko Sand, Zilpha Clay, Tallahatta Formation, and Meridian Sand of Mississippi are observed in the Macon and Moscow SE quadrangles. Upper Memphis Sand characteristics are seen in the northwestern two-thirds of the Macon map area The middle Memphis Sand characteristics are seen in the southern third of the Macon quadrangle and northern half of the Moscow SE quadrangle. The lower Memphis Sand characteristics are seen in the southeastern portion of the Moscow SE map area. The stratigraphic sequence of the members is consistent with the low regional dip of the strata to the northwest (Parks and Carmichael, 1990a).

Post-Eocene Terrace Deposition and Weathering

Overlying the Eocene Memphis Sand is a highly weathered gravelly sand deposit interpreted as a reworked terrace deposit. Its characteristics are similar to the Memphis Sand as a massive or cross bedded yellowish red or reddish yellow quartz sand, but it contains chert or iron oxide gravel. It contains common yellowish gray silty clay root traces. Two samples, Dog-1b and JC-5, into thin sectioned and show very similar characteristics to underlying or nearby Memphis Sand samples. These samples are quartz wacke because samples are 100 % quartz grains with greater than 10 % matrix. Quartz grains are mostly monocrystalline quartz with some polycrystalline quartz. Although these samples have chert gravels associated with them, the average amount of polycrystalline quartz is the same as samples of Memphis Sand (Table 3). Monocrystalline quartz in these deposits have the same characteristics of the monocrystalline quartz in the Memphis Sand; some grains are angular, contain inclusions, and have an embayed shape. Although it is quartz-dominated, the terrace deposits include much of the same accessory minerals found in the upper Memphis Sand, such as zircon, kyanite, rutile, sillimanite, biotite, tourmaline, and horneblende indicating the possibility that these are a reworked unit with addition of chert or iron oxide gravels. These reworked terrace deposits also have characteristics similar to the Upland Complex, an interpreted Pliocene high-level fluvial terrace complex, and outcrops are found at elevations comparable to the elevations of the Upland Complex in neighboring Shelby County to the west (Van Arsdale et al., 2008). The Upland Complex overlies the Tertiary units and underlies the Quaternary Loess and modern Alluvium on the eastern side of the current Mississippi River from Illinois to Louisiana, and is characterized as a fluvial chert gravel commonly with limonite coatings with fine to coarse sands, silts, and clays. Therefore, the reworked terrace deposits in Fayette County appear to be correlative to the Upland Complex.

A paleosol is developed in the fluvial terrace deposits and another in the upper 2 to 3 m of Memphis Sand exposures. The two paleosols are typically overlain by a weakly developed modern soil in the loess. The younger paleosol, developed on the reworked terrace deposits, has B and Bt horizons and is a mottled, oxidized yellowish red weakly developed sandy loam and sandy clay loam with less than 10% gravel and common modern yellowish gray silty clay root traces. The older paleosol, developed on the Memphis Sand, has Bt and Cox horizons and is mottled, oxidized red moderately developed sandy loam and sand with secondary clay accumulation as grain coatings and pore fill, and common modern, yellowish gray silty clay root traces, and ancient, white clay or silty clay root traces.

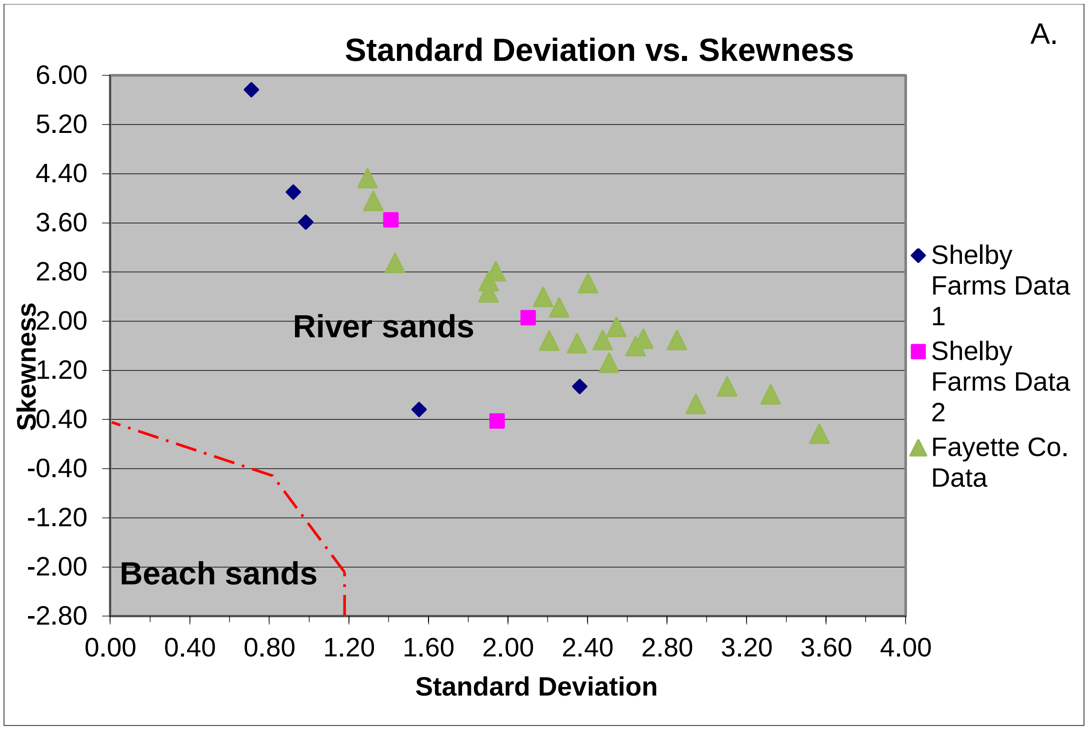
The paleosols have characteristics dependent on parent material, relief, and time. The parent materials of the paleosols are fluvial sands; however, the Memphis Sand was deposited much before late Cenozoic soil development. Fluvial sediment is subject to periods of deposition, erosion, and stability. However, to accumulate the amount of Fe and kaolinite clay present in the soils and their relative thickness, there must have been long periods of stability between incision and deposition in the terrain. The younger paleosol, found on terrace deposits, is thinner and the Fe is less developed indicating that the period of stability, even though long enough to develop the soil, was not as long as the period of stability for the older paleosol which is thicker and has well developed Fe and kaolinite clay. The absence of an A horizon in both paleosols demonstrate the unstable environment during the post-Eocene weathering and depositional history. The removal of the A horizon makes it difficult to assign a specific soil order for either of the paleosols. However, they could potentially have been ultisols based on the Bt and Cox horizons.

Regarding weathering, the most important pedogenic processes in these two paleosols are Fe and clay accumulation. Fe accumulation causes the rich red colors and also helps to flocculate and accumulate the clay particles (Birkland, 1999). Both paleosols contain abundant Fe oxide in the form of grain coatings and mixed in the secondary clay matrix. Fe oxide in the younger paleosol is more soluble in the sodium dithionite treatment (Table 1) (Gee and Bauder, 1986) and is most likely limonite or goethite. Whereas Fe oxide in the older paleosol is less soluble by the same treatment and a deeper red color, both of which are more consistent with hematite.

Clay accumulates by both *in situ* alteration of silicates into clay minerals and the translocation of detrital material such as dust or *in situ* formed clay minerals (Birkeland, 1999). Pedogenic evidence in thin sections for clays that are translocated includes accumulation in voids, bridges, and/or grain coatings as clay bands or lamellae (Birkeland, 1999; Shaetzl and Anderson, 2005), which are abundant in thin sections from both the paleosols. Banding is slightly more abundant and thicker in the older paleosol. These bands typically consist of several thin layers of clay and pedogenic Fe (Birkeland, 1999). The clays can completely fill pore space or form a thin coating (Shaetzl and Anderson, 2005). These features are most common in sandy parent materials. Clay that forms in situ usually occupy the pitted margins of grains that were once smooth (Birkeland, 1999). Little or no evidence of clays forming *in situ* from mineral weathering is seen in any of the thin sections of the reworked terrace deposits or the Memphis Sand. This is possibly because the clay minerals formed higher in the soil profile (perhaps the A horizon, which is no longer present) and quickly migrated down to the Bt horizon. Lessivage of clay minerals occurs best during weathering in humid environments where water commonly infiltrates through the profile and carries down the clay particles (Shaetzl and Anderson, 2005).

Environment of Deposition

Outcrop features, particle size analysis, and clay mineralogy all support a fluvial environment of deposition. Outcrop scale features such as scour and fill structures, bank collapse features (brecciated clay intraclasts), and planar cross-bedding are consistent with fluvial depositional environments (Miall, 1996). Particle size analysis also indicates that the samples are entirely fluvial sands. Fluvial sands typically have less steep cumulative curves, larger standard deviation, and contain fines, whereas, beach sands have steep curves, small standard deviation and no fines (Friedman and Johnson, 1982). Figure 22a



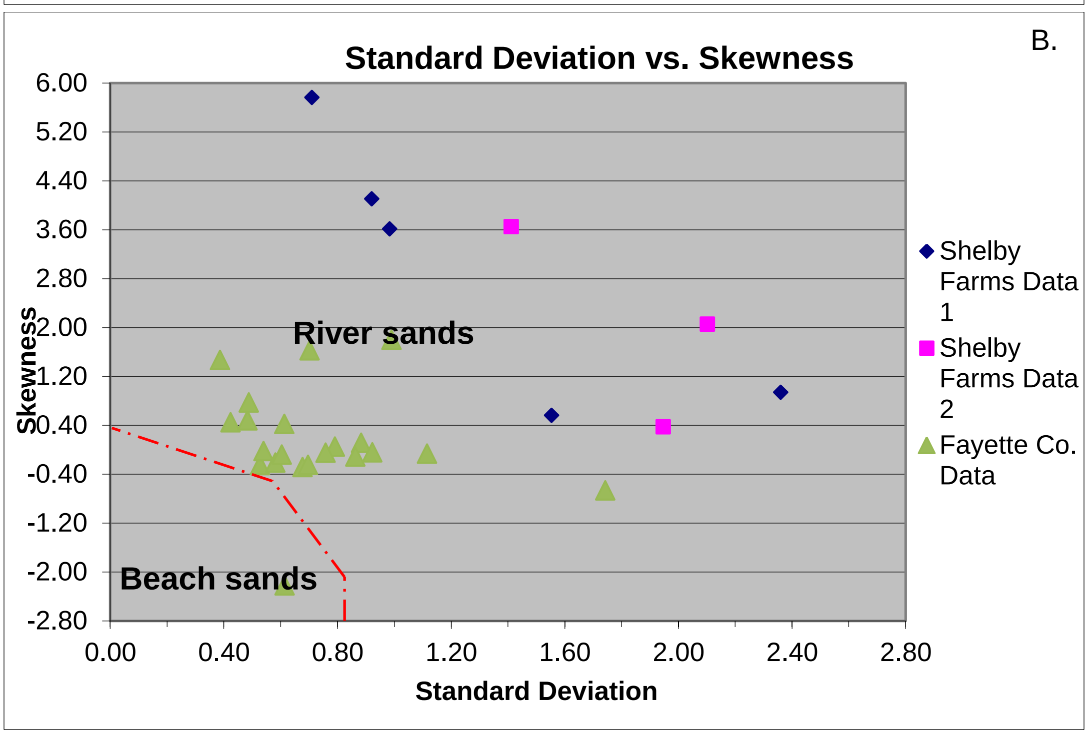


Figure 22. a. A scatter plot, with fines included, used to interpret the environment of deposition of sediments using the grain size statistics of skewness, which is influenced by grain size tailing, and standard deviation, which indicates sorting. b. A scatter plot, without fines included, used exclude the impacts of post-depositional weathering on the grain size data. (Friedman and Johnson, 1982)

shows a plot of standard deviation versus skewness for the Memphis Sand samples in comparison to previously collected samples (Gentry et al., 2006). The plot shows that all samples from this study, being poor to well sorted fine to coarse sands, fall within the river sands category. The fine fraction in these samples is almost entirely secondary clay that resulted from post-depositional soil processes. Once the fine fraction was removed sands are moderately to well sorted. With the fine fraction removed samples still fell within the fluvial sands category (Figure 22b). The grain sorting, erosional nature of some outcrop scale features, such as bank collapse breccias, and common cross beds favor a meandering channel environment (Miall, 1996). However, large planar cross beds, channel infill structures, and lack of point bar sequences favor a braided stream morphology.

Kaolinite with minor amounts of illite dominates the clay mineralogy found in the Memphis Sand. Kaolinite with varying amount of illite and smectite is the dominant clay mineralogy in the fluvial environments of the Claiborne in the Mississippi Embayment (Jeffers, 1982; White, 1985, Gentry et al., 2006). Therefore, the clay mineralogy observed from the clay beds and clay intraclasts found in the otherwise sandy outcrops of the Memphis Sand indicates that it is continental fluvial environment of deposition.

Provenance

Several sources have been suggested for the provenance of the Memphis Sand including the Appalachian Mountains (Stearns and Reesman, 1986), the Cretaceous Tuscaloosa Formations (Marcher and Stearns, 1962), the Ozark

Mountains (Saint Francois Mountains) of Missouri (Lumsden et al., 2009), or a combination of the Ozarks Mountains and the Cretaceous Tuscaloosa Formation (Hundt, 2008). Jeffers (1985), White (1982), and Potter and Pryor (1961) suggest that the source of the depositional clay is detrital material from the Blue Ridge and Piedmont Plateau of the Appalachian Mountains. Trace amounts of mica, kyanite, and zircon likely indicate a source area with granite, gneiss, and schists. Monocrystalline quartz grains commonly contain inclusions or embayed features indicate contributions from a volcanic source. Samples from the upper Memphis Sand contain traces of mica, zircon, and kyanite, with lesser amounts of rutile, tourmaline, sillimanite, and hornblende. Samples middle and lower Memphis Sand only contain traces of mica, kyanite, and zircon, but were more micaceous. This could be due to multiple sources or the same source but from different depositional events. The most important source for smectite, found in XRD patterns, is alteration of volcanic glass or ash (Moore and Reynolds, 1997), however, it could form in less humid climatic conditions or from shales (Velde, 1995). Cristobalite, found in Samples WR-3 and CC-1, also suggests alteration from volcanic material, possibly from ash fallout from volcanoes in New Mexico and Colorado (Reynolds, 1970). Reynolds (1970) found similar altered ashes in the Tallahatta of Mississippi, a unit that is coeval with the middle Memphis Sand. Sample WR-3 is the northern most clay bed found in the upper Memphis Sand, and sample CC-1 is from the clay intraclasts also found in the upper Memphis Sand indicating that these ash falls could have occurred during the latest Memphis Sand time as well as prior events.

The types of monocrystalline quartz and clay mineralogy all suggest primarily volcanic source, the remnant silica overgrowths and angularity of the grains suggest a sedimentary source, and the trace minerals and polycrystalline quartz suggest igneous and metamorphic rocks could be a part of the source. So it is possible that the Memphis Sand has a mixed source that is influenced by the St. Francois Mountains for the monocrystalline quartz, but a high pressure metamorphic environment like the Appalachian Mountains for the accessory minerals such as kyanite and sillimanite. Potter and Pryor (1964) note that these accessory minerals exist in the Paleozoic sandstones in the upper Mississippi Valley, but conclude that they are too abundant to be from a sedimentary origin and more truly represent the mica schists and gneisses of the southern Appalachian Mountains as a source area.

Implications for Recharge to the Memphis Aquifer

Overall, the outcrops of Memphis Sand and overlying terrace deposits are few and far between, spatially limiting the amount of direct recharge into the Memphis aquifer. The outcrops are found primarily in upland sandy bottom stream channels which tend to be dry a majority of the time, even after rain events. The dryness of these streambeds suggests that infiltration in these areas is likely to be rapid although spatially limited. Some of the coarser grained alluviated valleys exhibit dry streambed behavior suggesting that infiltration could occur in these areas as well. Recharge is further limited by weathering and accumulation of secondary clays in the paleosol profiles.

Porosity of the Memphis Sand is between 20 and 40 % (Table 1). This is attributed to the unconsolidated, uncompacted, and predominantly angular quartz composition that left a relatively open framework following deposition. Subsequently porosity in most samples becomes partially filled by secondary kaolinite and iron oxide matrix during post-depositional weathering (Lumsden et al., 2009). In samples of the terrace deposits and highly weathered sandy Memphis Sand outcrops (Table 3), however, the pore space is partially or completely filled with pedogenic clays, which comprises about 10 to 35 % of the sand-dominated samples, making the porosity as low as 5 %. Terzahgi et al. (1996) determine that with every 5 % increase in fines passing through a #200 sieve, permeability gets reduced by an order of magnitude. In most of the moderately weathered samples, the percent of matrix was between 5 and 15 %, which strongly limits recharge.

The weathering and soil development in the terrace deposits and Memphis Sand have significant effects on the potential for recharge. Both paleosols have strong Bt horizons. Bt horizons thicken over time and can eventually become aquitards or aquicludes as pores get plugged with illuvial clay (Shaetzl and Anderson, 2005). The deleterious effects of secondary clay infiltration and clogging on recharge are compounded where the weathered terrace gravel layer overlies the weathered Memphis Sand, creating two barriers to infiltration. B. Waldron and D. Larsen (Personal communication, D. Larsen) measured recharge at Pinecrest, a site in the Moscow SE, quadrangle using chloride mass balance profiles. The study suggests that recharge most likely occurs in stream gullies more during the wet season rather than by vertical infiltration through the loess and paleosols. In summary, recharge of the Memphis aquifer in the field area is limited by both the sparse exposure of Memphis Sand and clogging of pores by secondary clays attributed to weathering and soil development.

CONCLUSIONS

Lithological characteristics of the Eocene Memphis Sand in outcrops within the Macon and Moscow SE 7.5-minute quadrangles correlate well with the tripartite division of into the upper, middle, and lower Memphis Sand described by Hundt (2008) and Waldron et al. (2011). The informal members of the Memphis Sand also correlate well with lower Eocene strata of Mississippi (Dockery, 1996). The middle Memphis Sand is bounded on top and bottom by clay-rich layers which potentially correlate to the Zilpha Clay and the lower Tallahatta Formation.

The Memphis Sand is typically overlain by 1 to 2 m of gravel and sand interpreted to be reworked fluvial terrace deposits of the Pliocene Upland Complex (Van Arsdale et al., 2008).

Most exposures of the Memphis Sand and overlying terrace deposits show prominent paleosol development in the upper 2 to 3 m. The younger paleosol, developed on the terrace deposits, has B and Bt horizons depending on the amount of clay found in the layers. Both paleosols contain large amounts of secondary clay and iron oxides. In the younger paleosol the iron oxide accumulation is weakly developed and easily removed, but in the older paleosol it is well developed and difficult to remove. The paleosols are interpreted to be remnant ultisols; however, the A horizons have been removed from both.

The Eocene Memphis Sand is predominately a quartz arenite or quartz wacke, depending on the amount of secondary clay matrix present. Most samples have between 2 and 15 % matrix, but some samples have greater. Quartz grains are dominantly monocrystalline with sparse inclusions or embayed grains. Most samples contain about 5% polycrystalline quartz. Grains are fine to coarse sand and angular to rounded. Porosity ranges from 20 to 40 % depending on the amount of matrix, most of which is secondary. Secondary matrix due to post-depositional weathering is identified in thin section based on features such as bridges, banding, and meniscus boundaries. Greater quantities of matrix result in a lowered porosity because the matrix begins clogging the pore space. The clay mineralogy of the Memphis Sand is a mixture of kaolinite and illite with minor amounts of expandable clay. Accessory minerals determined from thin sections include muscovite, zircon, kyanite, biotite, rutile, sillaminite, tourmaline, and hornblende, with the greatest variety found in the upper Memphis Sand member.

The Memphis Sand in outcrop is mainly massive, cross-bedded, or laminated fine to coarse, well to poorly sorted sands with occasional clay clasts or beds. Based on depositional structures, petrographic features, and grain size distributions, the Memphis Sand was most likely laid down in a meandering to braided fluvial depositional environment. Grain size statistics fall within the river sands grain distributions of Friedman and Johnson (1982). Bank collapse breccias, channel forms, planar cross bedding and moderate to well sorted sand all support a meandering fluvial system. Channel infill features with thin layers of intermittent gravel and sand, lack of point bar sequences, and planar cross-bedding are more typical of braided streams (Boggs, 2006). Although point bar sequences are not observed, structures and sorting typical of braided systems were not observed either. Because of post-depositional weathering and massive structure present in most Memphis Sand outcrops, detailed analysis of the fluvial depositional processes may not be possible.

The provenance of the Memphis Sand is from a mixture of sources, potentially influenced by Precambrian volcanic rocks from the St. Francois Mountains of Missouri and metamorphic rocks of the southern Appalachian Mountains as well as recycling of younger clastic sedimentary rocks in the mid-continent. Monocrystalline quartz grains are highly angular and commonly contain inclusions or have an embayed morphology indicating that these sediments had to come from a nearby volcanic source, such as the St. Francis Mountains. Accessory minerals and polycrystalline quartz suggest a source that contains high pressure metamorphic and igneous rocks, most likely in the southern Appalachian Mountains. Although the same heavy minerals are found in the Paleozoic sedimentary rock facies in the northern Mississippi Valley, they are found in high concentrations that are more consistent with the southern Appalachian source. Clay mineralogy reveals that most clays in the clay beds and intraclasts are depositional, with some clays likely formed or influenced by the alteration of volcanic ash, perhaps sourced from the western part of the United States.

The outcrop distribution and lithological and sedimentological features of the Memphis Sand have direct bearing on the recharge processes to the Memphis aquifer. Direct recharge into the Memphis aquifer in the study area is limited by degree of exposure, pedogenic alteration, and depositional matrix. Outcrops of the Memphis Sand are sporadic and discontinuous and typically found in incised stream valleys. However, as the upland stream valleys are the focus of runoff, stream bed infiltration may be significant. On many of the outcrops modern soil horizons as well as paleosol development further restrict infiltration and recharge, especially where pedogenic clays or depositional matrix clog pores.

Chapter 4: Conclusions

This thesis investigated the Eocene Memphis Sand in the Macon and Moscow SE 7.5-minute quadrangles in Fayette County, Tennessee to better assess the stratigraphy and sedimentology of the Memphis Sand and assess the recharge potential to the Memphis aquifer. Mapping, field descriptions, sampling and petrologic studies were done to evaluate the Memphis Sand in this study area. The results were used to address the following questions in this study:

- Where does the Memphis Sand crop out?

The Memphis Sand crops out primarily in upland sandy bottom stream valleys. Outcrop areas are relatively small and discontinuous.

- Are the sedimentary facies of the Memphis Sand stratigraphically continuous across the outcrop region?

Facies found in the Macon and Moscow SE quadrangles conform to the tripartite division of the Memphis Sand suggested by Hundt (2008) and Lumsden et al. (2009). Evidence of the informal upper, middle, and lower members of the Memphis Sand is observed in outcrop. The northern portion of the Macon quadrangle is characteristic of the upper Memphis Sand having sands exhibiting crossbedding as well as massive or laminated bedding. Two thick clay rich facies found in the southeastern portion of the Macon Quadrangle and northern portion of the Moscow SE quadrangle that potentially correlate with the Zilpha Clay and Basic City Shale member bounding the middle portion of the Memphis Sand as described by Waldron et al. (2011) and Lumsden et al. (2009) are indicative of the middle member. Outcrops in the southeastern portion of the

Moscow SE quadrangle exhibit characteristics similar to the lower Memphis Sand. Outcrops are massive, cross-bedded or laminated fine to coarse, poor to well sorted, micaceous sands. A thin, 1 to 2 meter thick, gravelly sand unit interpreted as a fluvial terrace deposit overlies the Memphis Sand with unconformity at many outcrop locations. This layer is too thin and discontinuous to be mapped as a separate unit and, thus, was mapped as the Memphis Sand based on its similar lithology and close association. Two paleosols, ranging from 2 to 3 m in depth, have developed on the outcrops. An older paleosol developed on the Memphis Sand and a younger paleosol developed on the 1 to 2 m-thick fluvial terrace deposit that overlies the Memphis Sand.

- What are the depositional characteristics and sediment source of the Memphis Sand?

The Memphis Sand is interpreted to be a braided fluvial deposit based on outcrop-scale sedimentary structures that include sets of planar cross-bedding, lack of point bar sequences, and broad channel infills with intermittent sands and gravels. However, some meandering fluvial structures such as cut and fill and bank collapse features, as well as moderate to good sand sorting is seen in outcrop as well. A mixed sediment source is proposed for the Memphis Sand that includes the St. Francis Mountains in Missouri, the distant Appalachian Mountains, and recycled clastic sedimentary rocks in the mid-continent region.

- What does the map and the sediment analyses tell us about recharge to the Memphis aquifer?

Direct recharge into the Memphis Aquifer is limited to areas where the Memphis Sand is exposed or underlies porous, permeable surficial deposits. Spatially, outcrops of the Memphis Sand are small and discontinuous except for one location on the northern side of the south fork of the Wolf River in the Moscow SE quadrangle. Paleosol development on the Memphis Sand and overlying fluvial terrace deposits limits vertical infiltration because pores are commonly clogged with accumulated clays and iron oxides.

References

Birkland, P. W., 1999, Soils and Geomorphology – 3rd Ed.: New York, NY. Oxford University Press Inc., 430p.

Boggs Jr., S., 2006. Principles of Sedimentology and Stratigraphy – 4th ed.: Upper Saddle River, NJ, Pearson Prentice Hall, 662 p.

Brock, C. and D. Larsen, 2010, Geologic mapping of the Eocene Memphis Sand, western Tennessee, and implications for recharge processes for the Memphis aquifer, South-Central Regional Geological Society of America Conference, New Orleans, LA.

Brock, C. and D. Larsen, 2011, Geological control of recharge processes in the Memphis aquifer in western Tennessee: field mapping and sedimentological data, Geological Society of America Conference, Minneapolis, MN.

Crone, A., 2010, Lithology in the Upper Claiborne confining unit in Shelby County and adjacent counties in Tennessee and Mississippi [Master's thesis]: Memphis, University of Memphis, 55p.

Cushing, E.M., E.H. Boswell, and R.L. Hosman, 1964, General Geology of the Mississippi Embayment, Water Resources of the Mississippi Embayment: United States Geological Survey Professional Paper 448-B, 28 p.

Dockery, D. III, 1996, Toward a Revision of the Generalized Stratigraphic Column of Mississippi: Mississippi Geology, Mississippi Department of Environmental Quality, Office of Geology, v. 17, no. 1., p. 1-9.

Flowers, R. L., 1964, *Soil Survey of Fayette County, Tennessee*: U.S. Department of Agriculture, U.S. Government Printing Office, 71 p.

Friedman, G. M. and K. Johnson, 1982, Exercises in Sedimentology: New York, NY, John Wiley and Sons Inc., 208 p.

Gee, G. W., and J. W. Bauder, 1986, Particle-Size Analysis, *in* A. Klute, ed., Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods: American Society of Agronomy, p. 383-411.

Gentry, R. W., The-Lung Ku, Shangde Luo, V. Todd, D. Larsen, and J. McCarthy, 2005, Resolving aquifer behavior near a focused recharge feature based upon synoptic wellfield hydrogeochemical tracer results: *Journal of Hydrology*, no. 323, p. 387-403.

Gentry, R. W., L. McKay, N. Thonnard, J. L. Anderson, D. Larsen, J. K. Carmichael, and K. Solomon, 2006, Novel Techniques for Investigating Recharge to the Memphis Aquifer: Tailored Collaboration 91137, Awwa Research Foundation, U.S.A., 97 p.

Hardeman, W. D., Miller, R. A., & Swingle, G. D. (1966). *Geologic map of Tennessee*. State of Tennessee, Department of Conservation, Division of Geology, 4 sheets.

Hosman, R.L., 1996, Regional stratigraphy and subsurface geology of Cenozoic deposits, Gulf Coastal Plain, South-Central United States: United States Geological Survey Professional Paper 1416-G, 35 p.

Hundt, K. R., 2008. Regional lithostratigraphic study of the Memphis sand in the northern Mississippi embayment [Master's thesis]: Memphis, University of Memphis, 104 p.

Jeffers, W.L., 1982, The Clay Mineralogy of the Claiborne Formation in West Tennessee [Unpublished M.S. Thesis]: Memphis, Tennessee, University of Memphis, 36 p.

Larsen, D., E. W. Spann, D. M. McClure, and R. Gentry, 2003, Selected Sediment Properties of Quaternary Deposits, Shelby County, Tennessee: Implications for Contaminant Hydrogeology and Quaternary Stratigraphy, *Southeastern Geology*, v. 42, no. 2, p. 99-110.

Lumsden, D.N., K.R. Hundt, and D. Larsen, 2009, Petrology of the Memphis Sand in the Northern Mississippi Embayment: *Southeastern Geology*, v. 46, no. 3, p. 121-133.

Mancini, E. A., and B. H. Tew, 1991, Relationships of Paleogene Stage and Planktonic Foraminiferal Zone Boundaries to Litho Stratigraphic and Allostratigraphic Contacts in the Eastern Gulf Coastal Plain: *Journal of Foraminiferal Research*, v. 21, no. 1, p. 48-66.

Marcher, M.V. and R.G. Stearns, 1962, Tuscaloosa Formation in Tennessee: *GSA Bulletin*, vol. 73, no. 11, p. 1365-1386.

Miall, A. D., 1996, The Geology of Fluvial Deposits Sedimentary Facies, Basin Analysis, and Petroleum Geology: New York, NY, Springer, 582 p.

Moore, G. K., 1965, Geology and Hydrology of the Claiborne Group in Western Tennessee: Geological Survey Water-Supply Paper 1809-F, 44 p.

Moore, G.K. and D.L. Brown, 1969, Stratigraphy of the Fort Pillow test well, Lauderdale County, Tennessee: Tennessee Division of Geology Report of Investigations 26.

Moore, R. B., D. L. Dilcher, and M. A. Gibson, 2003, Paleoenvironment, Depositional Setting, and Plant Fossil Diversity Found in the Claiborne Formation (Middle Eocene) Clay Deposits of Western Tennessee: Field Trip Guidebook, Joint Meeting South-Central and Southeastern Sections Geological Society of America, Chapter 9, Tennessee Division of Geology, Report of investigations 51, p. 187-198.

Moore, D. M., and R.C. Reynolds, 1997, X-Ray Diffraction and the Identification and Analysis of Clay Minerals -- 2nd ed.: New York, NY, Oxford University Press Inc., 371 p.

Parks, W. S., 1990, Hydrogeology and preliminary assessment of the potential for contamination of the Memphis aquifer in the Memphis area, Tennessee: Water-Resources Investigations Report 90-4092, 44 p.

Parks, W.S. and J.K. Carmichael, 1989, Geology and ground-water resources of the Fort Pillow Sand in western Tennessee: Water-Resources Investigations Report 89-4120, 25 p.

Parks, W. S. and J. K. Carmichael, 1990a, Geology and ground-water resources of the Memphis sand in western Tennessee: Water-Resources Investigations Report 88-4182, 34 p.

Parks, W. S. and J. K. Carmichael, 1990b, Geology and ground-water resources of the Cockfield formation in western Tennessee: Water-Resources Investigations Report 88-4181, 22 p.

Potter, P.E. and W.A. Pryor, 1964, Dispersal Centers of Paleozoic and Later Clastics of the Upper Mississippi Valley and Adjacent Areas: *GSA Bulletin*, v. 72, no. 8 p. 1195-1249.

Pryor, W.A and H.D. Glass, 1961, Cretaceous-Tertiary Clay Mineralogy of the Upper Mississippi Embayment: *Journal of Sedimentary Petrology*, vol. 31, no. 1, p. 38-51.

Reynolds, W.R., 1970, Mineralogy and Stratigraphy of Lower Tertiary Clays and Claystones of Alabama: *Journal of Sedimentary Petrology*, vol. 40, no. 3, p. 829-38.

Russell, E.E., and Parks, W.S., 1975, Stratigraphy and outcropping Upper Cretaceous, Paleocene, and Lower Eocene in Western Tennessee (including descriptions of younger fluvial deposits): State of Tennessee Department of Conservation, Division of Geology, Bulletin 75, 37 p.

Saucier RT. 1987. *Geomorphological interpretation of Late Quaternary in western Tennessee and their regional tectonic implications*: U.S. Geological Survey Professional Paper 1336-A.

Shaetzl, R. and S. Anderson, 2005, Soils Genesis and Geomorphology: New York, NY, Cambridge University Press, 817 p.

Stearns, R.G., 1957, Cretaceous, Paleocene and lower Eocene Geologic History of the Northern Mississippian Embayment: *GSA Bulletin*, v. 68, no. p. 1077-1100.

Terzaghi, K., Peck, R.B., Mesri, G., 1996. Soil mechanics in engineering practice (3rd edition), John Wiley and Sons, 549 p.

Van Arsdale, R.B., Bresnahan, R.P., McCallister, N.S., and Waldron, B., 2007, The Upland Complex of the central Mississippi River valley: Its origin, denudation, and possible role in reactivation of the New Madrid seismic zone, *in* Stein, S., and Mazzotti, S., eds., Continental intraplate earthquakes: Science, hazard, and policy issues, Geological Society of America Special Paper 425, p. 177-192.

Vestal, F.E., 1954, Marshall County Geology: Mississippi State Geological Survey Bulletin. no. 78, 193 p.

Waldron, B., D. Larsen, R. Hannigan, R. Csontos, J. Anderson, C. Dowling, J. Bouldin, 2011, Mississippi Embayment Regional Groundwater Study: United States Environmental Protection Agency, EPA 600/R-10/130, 192 p.

Webbers, A., 2003, Ground-water use by public water-supply systems in Tennessee, 2000: U.S. Geological Survey Open-File Report 03-47, 1 sheet.

White, M.D., 1985, The Clay mineralogy of the Claiborne Formation in Carroll and Weakley Counties, Tennessee [Unpublished M.S. Thesis]: Memphis, Tennessee, University of Memphis, 44 p.